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Vol. 2. Part 1 MARCH, 1921 Number 9

BULLETIN
OF THE
NATIONAL RESEARCH COUNCIL

UNIV. OF CALIFORNIA

FUNDS AVAILABLE IN 1920 IN THE UNITED STATES OF AMERICA FOR THE ENCOURAGEMENT OF SCIENTIFIC RESEARCH

COMPILED BY THE RESEARCH INFORMATION SERVICE,
NATIONAL RESEARCH COUNCIL

CALLIE HULL
TECHNICAL ASSISTANT

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
1921

Announcement Concerning Publications of the National Research Council

The Proceedings of the National Academy of Sciences

has been designated as the official organ of the National Research Council for the publication of accounts of research, committee and other reports, and minutes.

Subscription rate for the "Proceedings" is $5 per year. Business address: Home Secretary, National Academy of Sciences, Smithsonian Institution, Washington, D. C.

The Bulletin of the National Research Council

presents contributions from the National Research Council, other than proceedings, for which hitherto no appropriate agencies of publication have existed.

The "Bulletin" is published at irregular intervals. The subscription price, postpaid, is $5 per volume of approximately 500 pages. Numbers of the "Bulletin" are sold separately at prices based upon the cost of manufacture (for list of bulletins see third cover page).

The Reprint and Circular Series of the National Research Council

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BULLETIN
OF THE
NATIONAL RESEARCH COUNCIL

VOLUME 2

March, 1921, to July, 1921, inclusive

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COMPILED BY THE RESEARCH INFORMATION SERVICE,
NATIONAL RESEARCH COUNCIL
CALLIE HULL, TECHNICAL ASSISTANT

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I. INTRODUCTION

The Research Information Service of the National Research Council has assembled data concerning funds which are variously available for the support or encouragement of scientific research. It is planned to maintain an up-to-date file on this subject in the offices of the Research Council for the benefit alike of correspondents and of the Divisions of the Council. This bulletin is issued in order to render information concerning funds immediately and widely available to those interested in scientific research.

The funds listed are classified primarily according to use and secondarily according to institution. Under use, the categories employed in this bulletin are medals, prizes, grants, institutional funds, fellowships and scholarships. Federal and State funds for research are not included. The term institution is used throughout this bulletin to designate those nine types of organization which are grouped in three categories, as follows: A. Academies, associations, societies, and museums; B. Foundations, hospitals, and research institutes; C. Universities and colleges. In each of the informational sections of the bulletin the data are arranged under institutions. A list of funds with essential information is presented under each institution. Section II presents data concerning medals and prizes available for the encouragement of research; Section III contains information concerning grants which are made, upon application, to individuals or institutions who desire to conduct a scientific investigation. Section IV similarly presents information concerning funds which are available for the support of research only within the institution or organization by which they are administered. Section V is devoted to those fellowships and scholarships in connection with which research is specifically mentioned. In Section VI, a subject index, are listed all of the funds which are known to be available for the support or encouragement of research in the biological, mathematical, and physical sciences and their applications. Section VII indexes all institutions mentioned in the bulletin and those funds which have distinctive titles. The latter are indicated by the last name, followed by the first name in parenthesis, as, for example, the Sloane (Thomas C.) Fund.

So far as possible, information has been obtained by direct appeal to the institutions which hold and adminster research funds. Where this was impossible, the latest available reports, yearbooks, or catalogues have been consulted and institutions have been requested to verify and supplement the data of the Research Information Service. In most instances the information published herein is for the year 1920.

In Sections II and VI only those medals, prizes, fellowships and scholarships are included in connection with which specific mention of research is made. Ordinarily, this occurs in the name of the prize, medal, fellowship or scholarship, or in the announcement of terms of award. It is highly probable there are many additional graduate fellowships and scholarships which are regularly used for the support of scientific research, although no mention is made of that fact in the catalogue or yearbook.

Despite all efforts to render this list of funds complete and correct, it is certain that many errors and omissions exist. The Research Information Service will greatly appreciate the coöperation of the authorities of those organizations which hold or administer research funds and of all other readers of this bulletin in reporting any errors or omissions which they discover.

II. MEDALS AND PRIZES FOR RESEARCH

A. Academies, Associations, Societies and Museums; B. Foundations, Hospitals and Research Institutes; C. Universities and Colleges

A—ACADEMIES, ASSOCIATIONS, SOCIETIES AND MUSEUMS

Academy of Natural Sciences, Logan Square, Philadelphia, Pa.

HAYDEN MEMORIAL GEOLOGICAL MEDAL, for distinguished work in geology or paleontology. Triennial.

American Academy of Arts and Sciences, 28 Newbury St., Boston, Mass.
RUMFORD PREMIUM, for research on light and heat carried on in America. Established, 1796. Original fund, $5,000. Present fund, $67,072.05. Annually available, two medals and a fund not exceeding $300.

American Academy of Medicine, Jenkins Arcade, Pittsburgh, Pa.
McINTIRE PRIZE, for best essay on "The effect of child labor on the growth of the child" (1921 topic). Established, 1918. Triennially available, $250. (In 1922 this will probably be transferred to Lafayette College, Easton, Pa.)

American Association of Variable Star Observers, W. T. Olcott, Secretary, Norwich, Conn.
DAVID B. PICKERING NOVA MEDAL, for the first discoverer of a Nova. Established, 1918.

American Chemical Society, Chicago Section, R. J. Quinn, Secretary, 3314 West 67th St., Chicago, Ill.
WILLARD GIBBS MEDAL, for eminent work in and original contributions to pure or applied chemistry. Established, 1911. Present fund, $7,500.

American Chemical Society, New York Section, 17 Battery Place, New York City.
WILLIAM H. NICHOLS MEDAL, for meritorious research in organic chemistry. Established, 1902. Present fund, $1,700. Annually available, $98.00.

American Electrochemical Society, S. S. Sadtler, Secretary, 39 South 10th St., Philadelphia, Pa.
FRENZEL PRIZE, for best essay on the rare minerals in America and their production. Annually available, $250.

American Gastro-Enterological Association, Augustana Hospital, Chicago, Ill.
FUND OF $1,000, for annual honoraria for meritorious research work in gastro-enterology. Established, 1920. Original fund, $1,000. Present fund, $1,000. Annually available, $1,000.

American Genetic Association, 511 Eleventh St. N. W., Washington, D. C.
FRANK N. MEYER MEMORIAL MEDAL, for distinctive service in plant introduction. Established, 1918. Original fund, $1,000.

American Geographical Society, Broadway at 156th St., New York City.
CHARLES P. DALY MEDAL, awarded to explorers, writers and men of science who have contributed to the advance of geographical knowledge. Established, 1902. Original fund, $5,000. Awarded from time to time.

CULLUM GEOGRAPHICAL MEDAL, for distinguished service in geographical discovery or in advancement of geographical science. Established, 1896. Original fund, $5,000. Awarded from time to time.

DAVID LIVINGSTONE CENTENARY MEDAL, for scientific achievement in the field of geography of the Southern hemisphere. Established, 1913.

S. F. B. MORSE MEDAL, for encouraging geographical research. Established, 1903. Original fund, $1,000.

American Institute of Electrical Engineers, 33 West 39th St., New York City.
EDISON MEDAL, for meritorious achievement in electrical science, electrical engineering, or the electrical arts. Established, 1904. Original fund, $5,000. Annually available, $250.

American Institute of Homeopathy, 22 East Washington St., Chicago, Ill.
PHI ALPHA GAMMA GOLD MEDAL, for thesis based on original research, medical or surgical discovery.

American Institute of Mining and Metallurgical Engineers, 29 West 39th St., New York City.
PRESIDENT'S PRIZES, for best essays on some subjects relating to mining, economic geology, or metallurgy, by Junior Associate, or a member of an affiliated society. Special weight given to originality of investigation. Annually available, $30 and $20.

American Laryngological Association, 1021 Prospect Ave., Cleveland, Ohio.
DE ROALDES PRIZE (gold medal), to advance the science of laryngology and rhinology, in the United States and Canada, the medal is given to writer of original thesis. Established, 1908. Original fund, $500. Present fund, $700. Triennial.

American Laryngological, Rhinological, and Otological Society, Dr. W. H. Haskins, Secretary, 40 East 41st St., New York City.
ORIGINAL RESEARCH FUND, for the encouragement of research in laryngology, rhinology and otology. For essay written by members only. Original fund, $500. Annually available, $500 or part of it.

American Ophthalmological Society, 1819 Chestnut St. Philadelphia, Pa.
MEDAL FOR RESEARCH, in ophthalmology. Not confined to members. Established, 1919. Original fund, $1,500. Present fund, $1,500.

American Ornithologists' Union, T. S. Palmer, Secretary, 1939 Biltmore St. N. W., Washington, D. C.
BREWSTER MEMORIAL FUND, to encourage research in ornithology by an honorarium and medal to the author of the most important contribu-

tion to the subject during the two preceding years. Established, 1919. Original fund, $5,200. First award in 1921.

American Pharmaceutical Association, 115 West 68th St., New York City.
EBERT PRIZE FUND, for essay containing an original investigation of medicinal substance, or for improved methods of determining merit. Established, 1873. Original fund, $500. Present fund, $1,181.94. Annually available, $25.

American Philosophical Society, 104 South 5th St., Philadelphia, Pa.
MAGELLANIC GOLD MEDAL, for best discovery or invention annually in navigation, astronomy, or natural history. Established, 1786. Original fund, 200 guineas. Present fund, $3,500. Annually available, $139.25 (1918).

American Psychological Association, Edwin J. Boring, Secretary, Clark University, Worcester, Mass.
THOMAS A. EDISON PRIZE, for the most meritorious research on the effects of music in order to direct attention toward the importance of research in the psychology of music. Established, 1920. Original fund, $500. Present fund, $500. This prize is offered only for the year ending June 1, 1921 (for information regarding this prize address W. V. Bingham, Carnegie Inst., of Technology, Pittsburgh, Pa.).

American Roentgen Ray Society, Dr. H. E. Potter, Secretary, 122 South Michigan Ave., Chicago, Ill.
PRIZE OF $1,000, for the most meritorious research in the field of radioactive substances. Established, 1920. Offered for 1920–21 only.

American Society of Civil Engineers, 220 West 57th St., New York City.
COLLINGWOOD PRIZE, for a paper describing an engineering work with which the writer has been directly connected, or a record of investigations contributing to engineering knowledge, some essential part of which was made by the writer. Restricted to Juniors of the Society. Established, 1894. Annually available, $50.

JAMES R. CROES MEDAL, for a paper next in merit to that paper to which the Norman medal (q.v.) is awarded, and with same object. Established, 1912. Annually available, $40.

NORMAN MEDAL, for a paper which shall be judged worthy of special commendation for its merit as a contribution to engineering science. Restricted to members.

Association of Military Surgeons of the United States, Army Medical Museum, Washington, D. C.
HENRY S. WELLCOME PRIZES (2 medals), for essays on prescribed sub-

jects. Restricted to Medical Officers and former Medical Officers of the Army, Navy, Public Health Service, Organized Militia, United States Volunteers, and of the Reserves of the United States Army.

Astronomical Society of the Pacific, San Francisco, California.

BRUCE MEDAL, for distinguished service in astronomy. Established, 1897. Present fund, $3,300. Annually available, $159.82.

DONAHOE COMET MEDAL, for the discovery of an unexpected comet. Established, 1890. Present fund, $1,000. Annually available, $38.30.

Boston Society of Natural History, 234 Berkeley St., Boston, Mass.

WALKER GRAND PRIZE, for discovery and investigation. Quinquennially available, $1,000.

WALKER PRIZES (2), for best memoirs on subjects in natural history, to serve as an encouragement to the younger naturalists. Annually available, $100 and $50.

Boylston Medical Committee, Dr. W. F. Whitney, Chairman, Harvard Medical School, Boston, Mass.

BOYLSTON MEDICAL PRIZE AND GOLD MEDAL, for best essay which has original merit, on results of research in medicine, submitted on or before January 1, 1923. Open to all. Established, 1800. Triennially available, $500.

Cleveland Medical Library Association, 2318 Prospect Ave., Chicago, Ill.

HAMILTON F. BIGGAR PRIZES (3), for best essay on clinical subject. Biennially available, $600.

Franklin Institute, 15 South 7th St., Philadelphia, Pa.

BOYDEM PREMIUM, for research in the velocity of light waves. Original fund, $1,000.

CRESSON MEDAL, for discoveries. Established, 1848. Original fund $1,000.

JOHN SCOTT MEDAL FUND,* medal and premiums awarded from time to time for useful inventions that will advance chemical, medical, or any other science, or promote the development of industry in any form. Established, 1816. Original fund, about $4,000. Present fund, about $100,000. Annually available, $4,000 or more.

FRANKLIN MEDAL, for research in physical science or technology, awarded without regard to country, to the individual whose efforts in the opinion of the Institute have done most to advance the knowledge of physical science or its applications. Established, 1914.

LONGSTRETH MEDAL, for invention. Established, 1890. Original fund, $1,000.

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* This fund is administered by the Philadelphia Board of City Trusts. Formerly awards were made on recommendation of the Franklin Institute.

Geographical Society of Philadelphia, 1520 Chestnut St., Philadelphia, Pa.
ELISHA KENT KANE MEDAL, for important geographical exploration or research made during the twenty-four months preceding the award. Established, 1893.

Glass Container Association of America, 3344 Michigan Ave., Chicago, Ill.
AWARDS (7), for theses submitted prior to June 10, 1921, to stimulate more general research along the lines of better preparation and packing of foods and beverages, and to increase our knowledge of changes induced by preparation or storage of such products. Established, 1920. Annually available, $50–$150.

Maryland Academy of Sciences, Baltimore, Md.
MEDALS, awarded from time to time in recognition of scientific work and civic service.

Masons, Kane Lodge, No. 454, 46 West 24th St., New York City.
KANE LODGE MEDAL, for those who by preeminent achievement have added to the knowledge of mankind in those parts of the earth's surface unexplored or undeveloped. Established, 1920. Original fund, $4,020.50.

Mining and Metallurgical Society of America, 115 Broadway, New York City.
GOLD MEDAL, for conspicuous professional or public service for the advancement of mining and metallurgy, or of economic geology; for the betterment of conditions, and the safety and health of workmen therein. Established, 1914.

Naples Table Association, Dr. Florence Sabin, Secretary, Johns Hopkins University, Baltimore, Md.
ELLEN H. RICHARDS RESEARCH PRIZE, for best thesis on a scientific subject, embodying new observations and conclusions based on independent laboratory research. Open only to women. Established, 1900. Original fund, $1,000. Present fund, $1,000. Biennially available, $1,000.

National Academy of Sciences, Washington, D. C.
AGASSIZ MEDAL (from Murray Fund), for contributions to oceanography. Established, 1911. Original fund, $6,000. Present fund, $6,000. Annually available, $335.

BARNARD GOLD MEDAL, for meritorious service to science. Quinquennially available, not less than $200.

CYRUS B. COMSTOCK PRIZE, for researches in electricity, magnetism and radiant energy. Established, 1907. Original fund, $11,300. Present fund, $12,406. Annually available, $822.

DANIEL GIRAUD ELLIOT MEDAL, awarded to author of leading publication of year in zoölogy or paleontology. Present fund, $8,000. Annually available, $442.

HENRY DRAPER MEDAL, for notable investigations in astronomical physics. Established, 1883. Original fund, $6,000. Present fund, $10,000. Annually available, $544.

J. C. WATSON MEDAL, for research in astronomy. Established, 1874, Original fund, $13,757. Present fund, $25,000. Annually available, $1,182.

LAWRENCE SMITH MEDAL, for important investigations of meteoric bodies. Established, 1884. Original fund, $8,000. Present fund, $10,000. Annually available, $605.

MARCELLUS HARTLEY PUBLIC WELFARE MEDAL, for eminence in applications of science in conservation, selection and distribution of food. Established, 1913. Original fund, $1,200. Present fund, $1,200. Annually available, $65.

MARY CLARK THOMPSON GOLD MEDAL, for most important services to geology and paleontology. Established, 1919. Original fund, $10,000.

National Anesthesia Research Society, T. T. Frankenberg, Secretary, 16 East Broad St., Columbus, Ohio.

PRIZE OF $200, for best work on anesthesia. Established, 1920. Original fund, $200. Present fund, $200. Annually available, $200.

National Geographic Society, Washington, D. C.

HUBBARD GOLD MEDAL, for distinguished geographical discovery and for important contributions to the world's knowledge. Established, 1888.

SPECIAL GOLD MEDAL, for distinguished geographical discovery and for important contributions to the world's knowledge. Established, 1888.

New York Academy of Medicine, 17 West 43rd St., New York City.

GIBBS MEMORIAL PRIZE. Present fund, $17,259. Annually available, $728.

New York State Association of the Medical Reserve Corps, U. S. A.,

GORGAS MEDAL, for the best essay showing original research in preventive medicine. Established, 1918. Open to members of the Medical Corps, U. S. A., of the organized militia, and to the Medical Reserve Corps. For information address Editor, Military Surgeon, Washington, D. C.

Safety Institute of America, 18 West 24th St., New York City.

SEAMAN MEDAL, for progress and achievement in promotion of hygiene and mitigation of occupational diseases.

SCIENTIFIC AMERICAN MEDAL, for invention of most efficient safety device.

Society of Chemical Industry, American Section, Allen Rogers, Secretary, Pratt Institute, Brooklyn, N. Y.

GRASSELLI MEDAL, for thesis presented before the Society and offering the most useful suggestions in applied chemistry.

PERKIN MEDAL, for the most valuable work in applied chemistry. Established, 1906.

Southern Medical Association, Dr. Seale Harris, Secretary, Birmingham, Ala.

RESEARCH MEDAL, for meritorious and original work, provided the member has made contributions to medical science of sufficient importance to merit this distinction. Established, 1912. Annually available, $20.

United Engineering Societies, Charles F. Rand, Secretary, Board of Award, 71 Broadway, New York City.

JOHN FRITZ MEDAL, for notable scientific or industrial achievement. No restrictions on account of nationality or sex.

Western Society of Engineers, 1735 Monadnock Block, Chicago, Ill.

ROBERT W. HUNT AWARD, for best paper on the manufacture and fabrication of steel, or its products. Restricted to members under 35.

B—FOUNDATIONS, HOSPITALS AND RESEARCH INSTITUTES

Smithsonian Institution, Washington, D. C.

HODGKINS GOLD MEDAL, for important contributions to the knowledge of the nature and properties of atmospheric air, or for practical applications of existing knowledge to the welfare of mankind. Established, 1893. Annually available, about $250.

LANGLEY MEDAL, for specially meritorious investigations in connection with the science of aerodromics and its application to aviation. Established, 1908. Annually available, about $250.

C—UNIVERSITIES AND COLLEGES

Chicago, University of, Chicago, Ill.

HOWARD T. RICKETTS PRIZE, for research in pathology and bacteriology. Established 1912. Original fund, $5,000. Present fund, $5,000. Annually available, $250.

MEDICAL SCHOLARSHIPS AS PRIZES TO UNDERGRADUATES, for research in medicine, or one of the sciences fundamental to it. Not limited to University. Annually available, 1st prize, $225; 2nd prize, $150; 3rd prize, $75.

MEDICAL SCHOLARSHIP AS PRIZE TO GRADUATE, to encourage research in medicine. Annually available, $225.

ROSENBERGER MEDAL, for achievement in research in authorship, invention, discovery, unusual public service, or anything deemed of great benefit to humanity. Not limited to University. Established, 1917. Present fund, $2,000. Annually available, $100.

Columbia University, New York City.

BARNARD GOLD MEDAL, rewarded on recommendation of National Academy of Sciences to any person who within the five preceding years has made a worthy discovery in physical or astronomical science, or such novel application of science as to be beneficial to the human race. (Also listed under National Academy of Sciences.) Quinquennially available, not less than $200.

COCK PRIZE, for the best thesis on puerperal fever. Established, 1915. Present fund, $1,000. Annually available, $50.62.

LOUBAT PRIZES, for best work in English on the history, geography, archaeology, ethnology, philology, or numismatics of North America. Topics must refer to events prior to 1776 or antiquarian research. Not restricted to the University. Established, 1892. Present fund, $7,000. Quinquennially available, 1st prize, $1,000; 2nd prize, $400.

SMITH PRIZE, for best essay on a subject assigned by the College of Physicians and Surgeons. Annually awarded, $100.

STEVENS PRIZE, for best medical essay covering original research. Not restricted to the University. Established, 1891. Present fund, $1,800. Triennially available, $200.

College of Physicians and Surgeons, John H. Girvin, Secretary, 22nd St., Philadelphia, Pa.

ALVARENGA PRIZE, for essay on medical subject. Not limited to the College. Annually available, $250.

Cornell University, Ithaca, New York.

CRANDALL PRIZES, for the encouragement of research in civil engineering. Established, 1916. Original fund, $2,500. Annually available, 1st prize, $100; 2nd prize, $25.

FUERTES GRADUATE MEDAL, for a meritorious paper written by a graduate student on some engineering subject. Established, 1893. Original fund, $500. Annually available, $25.

MESSENGER MEMORIAL PRIZE, for essay showing best research and most fruitful thought in the field of human progress or the evolution of civilization during some period of human history, or during human history as a whole. Established, 1902. Present fund, $5,000. Annually available, $250.

Harvard University, Cambridge, Mass.

BOWDOIN PRIZES, for dissertations in any special field of learning. Two prizes for dissertations in science. Established, 1791. Present fund, $36,707.21. Annually available, $1,835.21. ($200 for each prize.)

BOYLSTON PRIZE AND MEDAL, for best essay on results of research in medicine. Established, 1803. Triennially available, $500. Competition open to all.

FLATTERY MEDAL, for the person who makes a discovery in any branch of science resulting in greatest good to humanity in the prevention of disease or preservation of health in the broadest sense. Established, 1918. Original fund, $7,500. Annually available, Medal and $525. Competition open to all.

OTOLOGICAL PRIZE, for best thesis showing original work on an otological subject. Annually available, $25. Open to fourth year students.

ROBERT TREAT PAINE FUND, for rewards by medals or otherwise, for discovery of new comets, planets, or for essays on valuable subjects. Established, 1886. Present fund, $273,932. Annually available, $14,025.

Johns Hopkins University, Baltimore, Md.

SYLVESTER PRIZE (medal), for research in mathematics.

New York University, New York City.

WILLIAM A. HOE, JR., ENGINEERING PRIZE, for best work in sanitary investigation. Established, 1897. Original fund, $1,000. Annually available, $60.

Philadelphia Academy of Surgery, Philadelphia, Pa.

SAMUEL D. GROSS PRIZE, for best paper on some subject of surgical pathology or surgical practice, based on original investigation. Only restriction is that candidates must be American citizens. Established, 1886. Quinquennially available, $1,500.

Philadelphia College of Physicians and Surgeons. *See* **College of Physicians and Surgeons,** Philadelphia.

Princeton University, Princeton, N. J.

CHARLES IRA YOUNG MEMORIAL MEDAL, for excelling in research in electrical engineering. Awarded annually.

Williams College, Williamstown, Mass.

CLARK PRIZE SCHOLARSHIPS (2), for general ability and interest in scholarly research. Annually available, $1,000.

CONANT-HARRINGTON PRIZE, for interest in biological research. Applied toward table at Marine Biological Laboratory, Woods Hole, Mass. Annually available, $25.

III. GRANTS FOR RESEARCH

Funds generally available to individuals or Institutions to promote or encourage research in: A. Academies, associations, societies and museums; B. Foundations, hospitals and research institutes; C. Universities and colleges

A—ACADEMIES, ASSOCIATIONS, SOCIETIES AND MUSEUMS

American Academy of Arts and Sciences, 28 Newbury St., Boston, Mass.

RUMFORD FUND, for grants to carry on research in light and heat in America. Established, 1796. Original fund, $5,000. Present fund, $67,072. Annually available, a sum not exceeding $300.

C. M. WARREN FUND, for research in chemistry. Established, 1892. Original fund, $6,000. Present fund, $13,289. Annually available, $1,254.

American Association for the Advancement of Science, Burton E. Livingston, Permanent Secretary, Smithsonian Institution, Washington, D. C.
PERMANENT FUND, for grants for scientific research. Present fund, $118,424. Annually available, $4,000.

American Association of State Highway Officials, Chapel Hill, N. C.
SMALL FUNDS available to aid research in highway problems.

American Medical Association, Committee on Scientific Research, 535 North Dearborn St., Chicago, Ill.
APPROPRIATION FOR GRANTS, to further meritorious research in subjects relating to scientific medicine and of practical interest to the medical profession which otherwise could not be carried on to completion. Established, 1920. Annually available, $1,000 to $2,000 for grants of $100 to $400 each.

American Medical Association, Council on Chemistry and Pharmacy, 535 North Dearborn St., Chicago, Ill.
FUND OF COMMITTEE ON THERAPEUTIC RESEARCH, used in connection with chemical investigations conducted by accredited research workers. Annually available, $2,000.

American Microscopical Society, P. S. Welch, Secretary, University of Michigan, Ann Arbor, Mich.
SPENCER-TOLLES FUND, to stimulate and aid research in microscopic work. Restricted to members. Established, 1884. Original fund, $25. Present fund, $5,958. Annually available, $402.

American Museum of Natural History, 77th and Central Park West, New York City.
MORRIS K. JESUP FUND, for promotion of research, exploration and publication. Present fund, $6,672,323 (1918). Annually available, $278,036 (1918).

SPECIAL FUNDS ACCOUNT, used in part to aid research in natural history. Present fund, $53,884. Annually available, $24,600 (1918).

American Pharmaceutical Association, 115 West 68th St., New York City.
CENTENNIAL FUND, to aid in the prosecution of original investigations. Established, 1877. Original fund, $1,107. Present fund, $3,176.

FUND OF $450 to aid pharmaceutical research. Established, 1920.

RESEARCH FUND, to encourage investigation and research upon any subject relating to pharmacy or to the collateral sciences. Established, 1916. Original fund, $7,043. Present fund, $11,102. Annually available, fifty per cent of the income until the sum reaches $100,000, and then the entire income.

Association for Improving the Condition of the Poor, New York City. Occasional grants for research.

Association of American Geographers, Richard E. Dodge, Secretary, Storrs, Conn.
FUND OF $3,000 which this Association, in conjunction with the American Geographical Society, plans to allow to grow until the annual income is $200, when it will be available for the assistance of members in carrying on research.

Brooklyn Institute of Arts and Sciences, Brooklyn, N. Y.
BIOLOGICAL LABORATORY OF THE BROOKLYN INSTITUTE OF ARTS AND SCIENCES. Funds for biological research in the laboratory at Cold Spring Harbor, N. Y. Established 1890. Present fund, $27,500. Annually available, $2,500.

Ecological Society of America, Dr. A. O. Weese, Secretary, Albuquerque, N. M.
SMALL AMOUNTS for coöperative research on ecological problems difficult or impossible of solution in the hands of a single individual.

Elizabeth Thompson Science Fund Committee, Dr. W. B. Cannon, Chairman, Harvard Medical School, Boston, Mass.
ELIZABETH THOMPSON SCIENCE FUND, for use in the promotion of science through small grants, preference given to researches involving international coöperation. Established, 1885. Original fund, $25,000. Present fund, $26,000. Annually available, $1,200 (1916).

Entomological Society of America, J. M. Aldrich, Secretary, National Museum, Washington, D. C.
THOMAS SAY FOUNDATION, for the publication of scientific monographs. Present fund, $250.

Indiana Academy of Sciences, 324 S. Ritter Ave., Indianapolis, Ind.
RESEARCH ENDOWMENT FUND, for assistance in research. Investigations in pure science given preference. Established, 1919. (This plan has been adopted, but has not yet been put in operation.)

Institute of Radio Engineers, A. N. Goldsmith, Secretary, College of the City of New York, New York City.
MORRIS LIEBMANN MEMORIAL FUND, to encourage research and invention in the radio field. Established, 1919. Original fund, $10,000. Annually available, $425.

Museum of the American Indian, Broadway at 155th St., New York City.

HEYE FOUNDATION, for research in archaeology and ethnology of the American Aborigines. Secretary of the Foundation, Frederic K. Seward, 30 Broad St., New York City.

National Academy of Sciences, Washington, D. C.

A. D. BACHE FUND, for research in physical and natural sciences. Established, 1870. Original fund, $40,515. Present fund, $59,000. Annually available, $3,323.

BENJAMIN APTHORP GOULD FUND, for research in astronomy. Established, 1897. Original fund, $20,000. Present fund, $20,000. Annually available, $1,888.

HENRY DRAPER FUND, to aid research in astronomical physics. Established, 1883. Original fund, $6,000. Present fund, $10,000. Annually available, $544.

JAMES C. WATSON FUND, for research in astronomy. Established, 1874. Original fund, $13,757. Present fund, $25,000. Annually available, $1,182.

JOSEPH HENRY FUND, for original research in the sciences. Established, 1878. Original fund, $40,000.

LAWRENCE SMITH FUND, for important investigations of meteoric bodies. Established, 1884. Original fund, $8,000. Present fund, $10,000. Annually available, $605.

O. C. MARSH FUND, for research in natural science. Established, 1899. Original fund, $9,400. Present fund, $19,500. Annually available, $1,037.

WOLCOTT GIBBS FUND, for research in chemistry. Established, 1892. Original fund, $2,600. Present fund, $5,545. Annually available, $308.

National Canners Association, 1739 H St., N. W., Washington, D. C.

GRANTS, for chemical, bacteriological and technological research relating to the manufacture of canned foods, systematic study of food poisons as applied to canned foods, but not limited to this phase, and the study of botulism.

National Committee for Mental Hygiene, 50 Union Square, New York City.

STUDIES AND SURVEYS FUND, for surveys of the care and treatment of mental diseases, for studies in mental deficiency, and for studies in the psycho-pathology of crime. Established, 1912. Original fund, $50,000. Present fund, $60,000.

National Geographic Society, 16th and M Sts., Washington, D. C.

RESEARCH FUND, to collect original geographical knowledge by equipping and sending parties into the field. Established, 1888. Appropriation made by Committee on Research in each case.

National Research Council, 1701 Massachusetts Ave., Washington, D. C.
OCCASIONAL GRANTS for research in the natural and physical sciences.

New York Academy of Sciences, 77th St. and Central Park, West, New York City.
CENTENNIAL ENDOWMENT FUND, for scientific research when it reaches the sum of $100,000. Present fund, $8,327.
ESTHER HERMANN RESEARCH FUND, for research in any branch of science. Established, 1899. Original fund, $10,000.
JOHN STRONG NEWBERRY FUND, for research in geology, paleontology, botany or zoölogy. Established, 1897. Original fund, $1,200.

Research Corporation, 31 West 43rd St., New York City.
GRANTS, for distribution to educational institutions, other organizations, or to individuals for the advancement and promotion of scientific enterprizes.

Seismological Society of America, S. D. Townley, Secretary, Stanford, Calif.
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE FUND, for the immediate investigation of earthquakes occurring on the Pacific Coast in the United States. Established, 1919. Original fund, $250. ($250 was given in 1919 and 1920, and it is hoped that this will be made an annual contribution.)

United Engineering Societies, Engineering Foundation, 29 West 39th St., New York City.
AMBROSE SWASEY FUND, for the advancement of the engineering arts and sciences in all their branches to the greatest good of the engineering profession and for the benefit of mankind. Established, 1915. Original fund, $200,000. Present fund, $500,000.

United States Interdepartmental Social Hygiene Board, 1800 Virginia Ave., Washington, D. C.
SCIENTIFIC RESEARCH FUND, for the discovery of better medical methods in the prevention and treatment of venereal diseases. Established, 1918. Original fund, $100,000. Present fund, $25,000.

NOTE: This Federal fund is included as it is expended entirely without Federal agencies.

B—FOUNDATIONS, HOSPITALS AND RESEARCH INSTITUTES

Carnegie Institution of Washington, Washington, D. C.
MINOR GRANTS. Available for 1920, $117,050.

Subscription to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Engineering Foundation. *See* **United Engineering Societies.**

General Education Board, 61 Broadway, New York City.
APPROPRIATIONS are made to conduct educational research, using the word educational in its broadest significance.

John McCormick Institute for Infectious Diseases, Chicago, Ill.
FENGER MEMORIAL FUND, to aid medical investigation. Established, 1910. Present fund, $11,000. Annually available, $400 to $500.

Rockefeller Foundation, New York City.
APPROPRIATIONS are made to two types of agencies by the Rockefeller Foundation, *i. e.*, those agencies which it creates to carry out specific programs, and other existing organizations, unaffiliated with the Foundation, to which it makes appropriations in order to enable them to carry out specific programs. Annually available, about $15,000,000 (1918).

Rockefeller Institute for Medical Research, New York City.
GRANTS are made for a single academic year ending June 30, unless otherwise agreed, and are limited largely to the support of investigations related to studies conducted at the Institute.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Smithsonian Institution, Washington, D. C.
HODGKINS FUND, for the increase and diffusion of more exact knowledge in regard to the nature and properties of atmospheric air in connection with the welfare of man. Established, 1891. Original fund, $100,000. Present fund, $100,000. Annually available, $6,000 in small grants.

SMITHSONIAN INSTITUTION FUND, from which small grants are sometimes made to scientific investigators.

C—UNIVERSITIES AND COLLEGES

Bowdoin College, Brunswick, Me.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Bryn Mawr College, Bryn Mawr, Pa.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Butler College, Indianapolis, Ind.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

California, University of, Berkeley, Calif.
SCRIPPS INSTITUTION FOR BIOLOGICAL RESEARCH. Annual gift for research in marine biology. Annually available, $35,500.

Chicago, University of, Chicago, Ill.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Cincinnati, University of, Cincinnati, Ohio.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Clark University, Worcester, Mass.

ELIZA D. DODGE FUND, to aid graduate students engaged in research. Original fund, $1,000.

College of Physicians and Surgeons of Philadelphia, Philadelphia, Pa.

FUND OF $500, open to medical profession and men of science in the United States for report of research on a subject of general medicine.

Columbia University, New York City.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Connecticut College, New London, Conn.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Cornell University, Ithaca, N. Y.

AUGUST HECKSCHER FOUNDATION, for the promotion of research. Established, 1920. Original fund, $500,000.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Creighton University, Omaha, Neb.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Dartmouth College, Hanover, N. H.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Doane College, Crete, Neb.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Goucher College, Baltimore, Md.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Harvard University, Cambridge, Mass.

ADVANCEMENT OF ASTRONOMICAL SCIENCE FUND, for aiding work of astronomers in any part of the world. Established, 1901. Present fund, $4,263. Annually available, $491.

ADVANCEMENT OF ASTRONOMICAL SCIENCE FUND, for aiding astronomers in any part of the world. Established, 1902. Annually available, $1,013.

HENRY C. WARREN FUND, for carrying on exploration. Established, 1899. Original fund, $10,000. Present fund, $10,631. Annually available, $522.

SHALER MEMORIAL FUND, for original research in geology in the broadest sense, including paleontology, mineralogy, economic geology, etc., Established, 1907. Present fund, $38,691.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Hunter College, New York City.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Illinois, University of, Urbana, Ill.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

UNIVERSITY BIOLOGICAL EXPERIMENT STATION. Funds for biological research at the station at Havana, Ill.

Indiana, University of, Indianapolis, Ind.

UNIVERSITY OF INDIANA BIOLOGICAL STATION. Funds for biological research at the station at Winona Lake, Ind. Established, 1895.

Iowa, University of, Iowa City, Iowa.

OKOBOJI LAKESIDE LABORATORY. Maintained for three months during the summer exclusively for research work for the staff and graduate students.

Johns Hopkins University, Baltimore, Md.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Kansas, University of, Lawrence, Kan.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Knox College, Galesburg, Ill.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Lake Forrest College, Lake Forrest, Ill.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Leland Stanford Junior University, Stanford, Calif.

HOPKINS MARINE LABORATORY OF STANFORD UNIVERSITY. Funds for biological research in the laboratory at Pacific Grove, Calif. Established 1892. Annually available about $2,500.

Michigan, University of, Ann Arbor, Mich.

BIOLOGICAL STATION OF THE UNIVERSITY OF MICHIGAN. Funds for biological research in the laboratory at Topinabee, Mich.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Missouri, University of, Columbia, Mo.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Mount Holyoke College, South Hadley, Mass.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Oberlin College, Oberlin, Ohio.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Ohio State University, Columbus, Ohio.

LAKE LABORATORY. Funds for biological research in the laboratory at Put-in-Bay, Ohio. Established 1895. Annually available, $2,300.

Pennsylvania, University of, Philadelphia, Pa.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Philippines, University of, Manila, P. I.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Phillips Academy, Andover, Mass.

ROBERT SINGLETON PEABODY FUND, for American archaeology. Established, 1901. Original fund, $150,000. Present fund, $458,214.96. Annually available, $21,122.74.

Pomona College, Claremont, Calif.

LAGUNA MARINE LABORATORY. Funds for biological research in the laboratory at Laguna Beach, Calif. Established 1910. Original fund, about $6,000. Annually available, $500–$800.

Princeton University, Princeton, N. J.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Radcliffe College, Cambridge, Mass.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Rice Institute, Houston, Tex.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Rochester, University of, Rochester, N. Y.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Simmons College, Boston, Mass.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Smith College, Northampton, Mass.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

SUBSCRIPTION to the Stazione Zoölogica in Naples, for a research table.

Sophie Newcomb College, New Orleans, La.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Southern California, University of, Los Angeles, Calif.
VENICE MARINE BIOLOGICAL STATION. Funds for biological research in the station at Venice, Calif. Established 1910. Present fund, $6,000.

Trinity College, Hartford, Conn.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Tufts College, Tufts College, Mass.
HARPSWELL MARINE LABORATORY. Funds for biological research in the laboratory at Casco Bay, South Harpswell, Me.

Vassar College, Poughkeepsie, N. Y.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Vermont, University of, Burlington, Vt.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Washington, University of, Seattle, Wash.
PUGET SOUND MARINE STATION. Funds for biological research in the laboratory at Friday Harbor, Wash. Established 1904. Annually available, $5,500.

Washington University, St. Louis, Mo.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Wellesley College, Wellesley, Mass.
SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

SUBSCRIPTION to the Society for the Promotion of Laboratory Research on the Part of Women.

Wesleyan University, Middletown, Conn.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Western Reserve University, Cleveland, Ohio.

BUTLER FUND, for the publication of results of research in American History, including archaeology and ethnology. Established, 1893. Original fund, $1,000. Present fund, $1,000. Annually available, $60.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Wheaton College, Norton, Mass.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

Wisconsin, University of, Madison, Wis.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

UNIVERSITY OF WISCONSIN BIOLOGICAL STATION. Funds for biological research in the station at Madison, Wis.

Yale University, New Haven, Conn.

BAYARD DOMINICK FUND, for the scientific exploration of the South Pacific Ocean, to be administered by the Bishop Museum. Original fund, $40,000, all of which must be expended before June 1, 1921.

SUBSCRIPTION to Marine Biological Laboratory, Woods Hole, Mass., for research in biology.

IV. INSTITUTIONAL FUNDS FOR RESEARCH

Restricted to use in the institution holding or administering them: A. Academies, Associations, Museums and Societies; B. Foundations, Hospitals, and Research Institutes; C. Universities and Colleges.

A—ACADEMIES, ASSOCIATIONS, SOCIETIES AND MUSEUMS

Academy of Natural Sciences, Logan Square, Philadelphia, Pa.

GENERAL FUND, for research in the institution. Annually available, $45,000.

American Academy of Ophthalmology and Oto-Laryngology, Luther C. Peter, Secretary, 1529 Spruce St., Philadelphia, Pa.

RESEARCH FUND, for which conditions have not yet been determined. Established, 1920.

American Institute of Drug Proving, 616 Madison Ave., New York City.

RESEARCH FUND, for work on drugs. Original fund, $3,250. Annually available, $120.

American Society for Psychical Research, 44 East 23rd St., New York City.

ENDOWMENT FUND, for research in psychical and abnormal psychological phenomena. Established, 1905. Present fund, $175,000.

American Society of Heating and Ventilating Engineers, P. O. Box 1818, New York City.

RESEARCH FUND, for determining and disseminating engineering knowledge pertaining to the profession of heating and ventilating, and to the equipment and apparatus utilized by the profession at large. Established, 1919. Annually available, $21,267.50 for five years.

Bernice Pauahi Bishop Museum of Polynesium Ethnology and Natural History, Herbert E. Gregory, Director, Honolulu, Hawaii.

BAYARD DOMINICK FUND, for exploration in the South Seas. To be expended before July 1, 1921, $40,000.

CHARLES R. BISHOP FUND for research in science. Annually available, $35,000.

CHARLES R. BISHOP TRUST, for research in science, and to supplement the fund. Annually available, $40,000.

Brooklyn Institute of Arts and Sciences, Brooklyn, N. Y.

ROBERT B. WOODWARD FUND, for research purposes of the Museum. Present fund, $600,000.

California Academy of Sciences, San Francisco, Calif.

ENDOWMENT, to be used in part for research. Original fund, $1,000,000. Annually available, $20,540.55.

Carnegie Museum, Pittsburgh, Pa.

RESEARCH EXPENDITURE, for research in the museum. Annually available $25,000.

Mathematical Association of America, W. D. Cairns, Secretary-Treasurer, 27 King St., Oberlin, Ohio.

APPROPRIATION FROM GENERAL EDUCATION BOARD, for research on mathematical requirements. Established, 1920. Annually available, $25,000.

New York Entomological Society, C. W. Long, Secretary, Staten Island, N. Y.

PERMANENT FUND, which may be used for scientific research at the discretion of the directors. Established, 1917. Original fund, $500. Present fund, $1,100. Annually available, $50.

New York State Museum, University of the State of New York, Albany, N. Y.

RESEARCH FUND, for special research. Annually available, $3,000 to $5,000.

B—FOUNDATIONS, HOSPITALS AND RESEARCH INSTITUTES

Barnard Free Skin and Cancer Hospital, St. Louis, Mo.

CANCER RESEARCH FUND, for research in cancer. Present fund, $100,000.

Carnegie Institution of Washington, 16th St., N. W., Washington, D. C.

ENDOWMENT, for the encouragement in the broadest and most liberal manner of investigation, research and discovery, and the application of knowledge to the benefit of mankind. Established, 1902. Original fund, $10,000,000. Present fund, $22,120,000. Annually available:

APPROPRIATION to Department of Terrestrial Magnetism. Available for 1920, $203,426.52.

APPROPRIATION to Department of Meridian Astronomy. Available for 1920, $38,912.00.

APPROPRIATION to Nutrition Laboratory. Available for 1920, $52,432.39.

APPROPRIATION to Geophysical Laboratory. Available for 1920, $125,852.

APPROPRIATION to Department of Marine Biology. Available for 1920, $27,628.88.

APPROPRIATION to Department of Embryology. Available for 1920, $43,128.

APPROPRIATION to Department of Ecological Research. Available for 1920, $24,840.00.

APPROPRIATION to Eugenics Record Office. Available for 1920, $30,785.76.

APPROPRIATION to Department of Experimental Evolution. Available for 1920, $78,343.27.

APPROPRIATION to Department of Botanical Research. Available for 1920, $64,723.26.

APPROPRIATION to Mount Wilson Observatory. Available for 1920, $181,665.68.

Harriman Research Laboratory, Roosevelt Hospital, New York City.

ENDOWMENT FUND, for the promotion of research in medical and biological sciences. Established, 1912. Annually available, $25,000.

John McCormick Institute for Infectious Diseases, 637 W. Wood St., Chicago, Ill.

W. A. CLARK FUND, for research in physiological chemistry.

RESEARCH FUND, for research in infectious diseases. Present fund, $2,000,000. Annually available, entire income.

Memorial Hospital, 106th St. and Central Park West, New York City.

COLLIS P. HUNTINGTON FUND, for research in cancer. Established, 1902. Original fund, $100,000. Annually available, $4,500. (From $2,500 to $5,000 added to this annually by the Huntington family.)

DOUGLAS FUND, for research in cancer. Established, 1917. Original fund, $100,000. Annually available, $5,000.

Metropolitan Life Insurance Company, New York City.

COMMUNITY HEALTH AND TUBERCULOSIS DEMONSTRATION FUND, for research in tuberculosis and general health fields. Present fund, $130,600.

INFLUENZA FUND, for research into the cause of the influenza epidemic. Established, 1919. Original fund, $50,000.

Montefiore Home and Hospital for Chronic Diseases, Gun Hill Road, N. Y. City.

SCHIFF RESEARCH LABORATORY FUND, for research in medicine. Established, 1909. Original fund, $100,000. Present fund, $200,000. Annually available, $10,000. ($300,000 will probably be added to the fund on the settlement of Mr. Schiff's will.)

WOLFF CANCER RESEARCH FUND, for the study of the cancer problem. Established, 1912. Original fund, $50,000. Present fund, $50,000. Annually available, $2,500.

Nelson Morris Memorial Institute for Medical Research, 2900 Ellis Ave., Chicago, Ill.

ORIGINAL GIFT, for laboratory research purposes. Established, 1910. Original fund, $500,000. Annually available, $5,000 from this fund and $17,000 in addition from the directors. (Not all of this is used for research, but must support the routine work of the hospital "Michael Reese," of which the Institute is a part.)

OTTO BAER FUND, for research in medicine. Established, 1920. Original fund, $200,000. Annually available, probably $10,000.

Robert D. Brigham Hospital for Incurables, Boston, Mass.

GOLDTHWAIT RESEARCH FUND, for scientific research. Established, 1915. Original fund, $60,000.

Rockerfeller Institute for Medical Research, 66th St. and Avenue A, New York City.

ENDOWMENT FUND, for medical research, with special reference to the prevention and treatment of disease. Established, 1901. Original fund, $20,000. Present fund, $23,000,000. Annually available, $1,100,000.

HENRY RUTHERFORD FUND, for cancer research. Present fund, $20,000. Annually available, $8,500.

Smithsonian Institution, Washington, D. C.

ENDOWMENT FUND, for the increase and diffusion of knowledge among men. Established, 1846. Original fund, $508,318. Present fund, $974,794.

Sprague Memorial Institute, Chicago, Illinois.
FUND, for medical research. Present fund, $1,500,000. Annually available, $80,000.

Trudeau Foundation, Saranac Lake, N. Y.
TRUDEAU FOUNDATION FUND, for research and teaching in tuberculosis. Present fund, $240,427. (1918.)

Trudeau Sanatorium, Saranac Lake, N. Y.
E. H. HARRIMAN MEDICAL AND RESEARCH FUND, for research in tuberculosis. Present fund, $27,355 (1918).

OLIVIA SAGE MEDICAL AND RESEARCH FUND, for research in tuberculosis. Present fund, $52,408. (1918.)

C—UNIVERSITIES AND COLLEGES

Amherst College, Amherst, Mass.
TUCKERMAN FUND, for the encouragement of the study of botany at Amherst. Established, 1915. Original fund, $5,000. Annually available, $200.

California Institute of Technology, Pasadena, Calif.
CHEMICAL RESEARCH FUND, for research in chemistry. Established, 1915. Present fund, $200,000. Annually available, $10,000.

PHYSICAL RESEARCH FUND, for research in the physical sciences. Established, 1916. Present fund, $200,000. Annually available, $8,350.

California, University of, Berkeley, Calif.
ALEXANDER FUND, for zoölogical research in the California Museum of Vertebrate Zoölogy. Annually available, $43,000.

AMERICAN MEDICAL SOCIETY FUND, for research in anatomy. Available in 1920, $400.

AMERICAN RED CROSS FUND, for research in anatomy. Available 1920, $3,000.

CITRUS FRUIT GROWERS FUND, for investigations in citrus fruits. Annually available, $2,200.

FRIEND OF UNIVERSITY FUND, for research in paleontology. Established, 1920. Annually available, $5,000.

GENERAL BUDGET APPROPRIATION, for research in all departments except those of agriculture and medicine. Established, 1920. Annually available, $20,000.

GENERAL BUDGET APPROPRIATION, for specific allotments for research Annually available, $12,000.

GIFT, for research. Available 1920, $2,500.

GIFT, for research in anatomy. Available 1920, $1,000.

HOOPER FOUNDATION, for research in medicine. Established, 1913. Annually available, $43,000.

LEMON MEN'S CLUB FUND, for investigation of lemons. Annually available, $2,880.

LICK OBSERVATORY FUND (including income on endowment, annual gifts and provision in university budget), for research in astronomy. Established, 1875. Annually available, $57,300.

MEDICAL SCHOOL FUNDS, for medical research. Annually available, $20,000.

NATIONAL CANNERS' ASSOCIATION FUND, for investigation of botulism. Annually available, $15,800.

PETALUMA POULTRYMEN'S FUND, for poultry investigation. Annually available, $2,000.

RESEARCH BOARD SPECIAL FUND, to aid special requests for research. Annually available, $4,000.

SAN FRANCISCO DENTAL SOCIETY FUND, for research in dentistry. Available 1920, $1,200.

U. S. INTERDEPARTMENTAL SOCIAL HYGIENE BOARD FUND, for research in pathology. Annually available, $3,875.

UNIVERSITY RESEARCH FUND ON SEARLES FOUNDATION, for research. Annually available, $12,000.

Case School of Applied Science, Cleveland, Ohio.

PHILIP RHODES McCURDY FUND, for the use of seniors in chemistry for research. Annually available, $1,000.

Chicago, University of, Chicago, Ill.

FLEISCHMAN COMPANY FUND, for investigating some of the scientific questions which have arisen in the manufacture of compressed yeast. Established, 1918. Annually available, $750.

GENERAL FUND APPROPRIATION FOR YERKES OBSERVATORY, for research in astronomy. Annually available, $32,000.

HELEN CULVER FUND, for the spread of knowledge in the biological sciences. Established, 1895. Original fund, $1,000,000. Present fund, $797,185.90. Annually available, $35,860.

HYDE MEMORIAL FUND, for research in skin diseases and cancer. Established, 1917. Present fund, $25,000. Annually available, $2,500.

Clark University, Worcester, Mass.

SMITH-BATTLES FUND, for investigation of spiritualistic and allied phenomena. Present fund, $5,000.

Columbia University, New York City.

ANONYMOUS FUND, for surgical research. Established, 1918. Original fund, $15,000. Principal used for special research work.

DYCKMAN FUND, for the encouragement of biological research. Established, 1899. Present fund, $10,324. Annually available, $464.58.

EMIL C. BONDY FUND, for investigation into the cause, prevention and cure of cancer, and toward general research in medicine and surgery and their allied subjects. Established, 1916. Present fund, $100,000. Annually available, $4,500.

GEORGE CROCKER SPECIAL RESEARCH FUND, for cancer research. Established, 1911. Present fund, $1,441,298. Annually available, $70,317.51.

LEE FUND, for research and equipment in the department of physiology. Established, 1914. Present fund, $20,000. Annually available, $900.

VANDERBILT CLINIC ENDOWMENT FUND, for clinical teaching. Established, 1896. Present fund, $115,000. Annually available, $5,650.

WILLIAM RICHMOND PETERS, JR., FUND, for research in the department of civil engineering. Established, 1912. Present fund, $50,000. Annually available, $2,250.

WILLIAM T. BULL MEMORIAL FUND, for original research under the direction of the department of surgery. Established, 1911. Present fund, $32,234. Annually available, $1,333.68.

Cornell University, Ithaca, N. Y.

AUGUST HECKSCHER FOUNDATION, for the promotion of research in Cornell, and the publication of results. Established, 1920. Original fund, $500,000. Annually available, $20,000.

FUND FOR RESEARCH IN VETERINARY MEDICINE, for investigation of the diseases of breeding cattle. Established, 1916. Annually available, $6,000.

FUND FOR RESEARCH IN VETERINARY MEDICINE, for investigation of the diseases of sheep, poultry and rabbits. Established, 1920. Annually available, $36,000.

FUND FOR VETERINARY EXPERIMENT STATION, for research and investigation in veterinary medicine. Annually available, $2,000 to $3,000.

RING MEMORIAL FUND, for the advancement of horticultural science. Established, 1913. Original fund, $1,000. Annually available, $50.

SARAH MANNING SAGE BEQUEST, to promote the advancement of medical science by encouragement of research at Ithaca. Established, 1915. Original fund, $50,000. Annually available, $2,571.

SUSANNAH PHELPS GAGE FUND, for research in physics. Established, 1918. Original fund, $10,000. Present fund, $10,000. Annually available, $514.

Denison University, Granville, Ohio.

EUGENE J. BARNEY FOUNDATION, for research—unlimited. Annually available, $5,000.

George Washington University, Washington, D. C.

Cooper Medical Research Fund, for investigations upon the nature, causes, etc., of malaria and other infectious diseases. Established, 1905. Present fund, $10,000. Annually available, $4,000.

Harvard University, Cambridge, Mass.

Aesculapian Club Gift, for research in the department of syphilology. Present fund, $190.

Anonymous Fund, for research in physical and inorganic chemistry in the Wolcott Gibbs Laboratory. Original fund, $5,000. Present fund, $5,055.48. Annually available, $55.48.

Bowditch Fund, for the promotion of original investigations in the physiological laboratory of the Harvard Medical School. Established, 1889. Original fund, $6,000. Present fund, $10.185. Annually available, $514.

Bullard Gift, for the study of pellagra, for use in the department of diseases of the nervous system. Present fund, $777. Annually available, $28.

Caroline Brewer Croft Fund, for researches and investigations in some effectual remedy or means of cure for cancer, consumption or other diseases generally supposed to be incurable. Cancer to receive preference. Established, 1899. Original fund, $92,025. Annually available, $4,711.

Colburn Fund, for research in tuberculosis. Established, 1919. Original fund, $97,052. Present fund, $99,298. Annually available, $2,246.

Coolidge Fund, for physical research. Established, 1901. Original fund, $57,500. Present fund, $17,417. Annually available, $950.

Cyrus M. Warren Fund, for the promotion of chemical research or the advancement of chemical science. Established, 1893. Original fund, $4,500. Present fund, $7,595. Annually available, $387.

Department of Tropical Medicine Research Fund, for research in tropical medicine. Present fund, $14,750.

Edward Austin Fund, for research in the bacteriological laboratory. Established, 1899. Original fund, $10,000. Present fund, $11,129. Annually available, $552.

Ernest B. Dane Fund, for research in physics. (Only part of the fund available for research.) Established, 1912. Present fund, $53,955. Annually available, $2,134.

Ernest B. Dane Fund, for research in sanitary engineering. Present fund, $1,124. Annually available, $32.

Expenses of Instruction and Investigation in Industrial Hygiene, in the department of preventive medicine and hygiene. Present fund, $98,350. Annually available, $3,943.

Flattery Research Fund, for cancer research. Established, 1915. Present fund, $11,800. Annually available, $800.

Francis C. Lowell Fund, for research in archaeology. Established, 1912. Present fund, $1,000. Annually available, $51.20.

Genetic Research Fund, for research in genetics. Present fund, $320.

Gift for Research, in the department of preventive medicine and hygiene. Present fund $25,711. Annually available $750.

Gift for Investigation of Infantile Paralysis, in the department of preventive medicine and hygiene. Present fund, $3,420. Annually available, $131.57.

Greenough Fund, for surgical research. Established, 1901. Original fund, $2,000. Present fund, $6,582. Annually available, $344.

Hemenway Fund, for original research in archaeology. Established, 1910. Original fund, $45,000. Present fund, $45,996. Annually available, $2,337.

Henry Isaiah Dorr Fund, for research in anesthetics. Established, 1917. Present fund, $100,000. Annually available, $3,950.

Herbert L. Burrell Fund, to further the art of science and surgery. Established, 1914. Present fund, $6.212. Annually available, $302.

Huntington-Frothingham-Wolcott Fund, for research in archaeology and ethnology, and for exploration and publication. Established, 1891 Original fund, $20,000. Present fund, $20,900. Annually available. $1,074.

Industrial Hygiene Fund, for study of health conditions in department stores, to be used in the department of preventive medicine and hygiene. Present fund, $3,183. Annually available, $33.65.

James C. Melvin Fund, for research in tropical medicine. Established. 1918. Original fund, $50,000. Present fund, $51,486. Annually available, $1,486.

Jefferson Coolidge Fund, for cancer research. Established, 1915. Present fund, $2,000. Annually available, $102.

Joseph de Lamar Fund, for the study and teaching of the origin and cause of disease and its prevention, and for the study and teaching of dietetics. Established, 1920. Original fund, $5,541,401.

Joseph Lovering Fund, for the promotion of original research at the Jefferson Physical Laboratory. Established, 1891. Original fund, $7,720. Present fund, $8,373. Annually available. $417.

Mears Fund, for the study of methods to reform and cure criminals and mental defectives by surgery. Established, 1919.

Memorial Cancer Hospital Research Fund, for research in cancer. Present fund, $11,458. Annually available, $458.

MERRILL WYMAN MEDICAL RESEARCH FUND, for investigation concerning origin, results, prevention and treatment of disease. Established, 1915. Present fund, $133,807. Annually available, $7,021.

PEABODY FOUNDATION FUND, for collection and research in archaeology and ethnology with special reference to the aboriginal American races. Established, 1905. Original fund, $45,000. Present fund, $119,214. Annually available, $5,805.

PROCTOR FUND, for promoting the study of chronic diseases. Established, 1903. Original fund, $50,000. Present fund, $51,809. Annually available, $2,620.

RESEARCH FUND OF GRAY HERBARIUM, for botanical research. Original fund, $300,000.

RESEARCH FUND, for medical research. Annually available, $350,000–$375,000.

RICHARD HODGSON MEMORIAL FUND, for psychical research. Established, 1912. Present fund, $14,794.27.

SURGICAL LABORATORY FUND, for research in surgery. Established, 1897. Original fund, $5,000. Present fund, $5,016. Annually available, $256.

SUSAN C. WARREN FUND, for research in archaeology. Established, 1902. Present fund, $10,631.35. Annually available, $256.

WALLACE C. SABINE MEMORIAL FUND, for the promotion of research in the department of physics. Restricted until it reaches a certain specified sum. Established, 1919. Present fund, $100,000.

WILLIAM J. AND GEORGIANA B. WRIGHT FUND, for medical research and the advancement of the medical and surgical sciences. Established, 1920. Original fund, over $23,000.

WILLIAM L. BRADLEY FUND, for scientific investigation to increase the knowledge of trees. Established, 1897. Original fund, $20,000. Annually available, $1,024.

ZOE D. UNDERHILL FUND, for research in medicine. Established, 1912. Present fund, $10,000. Annually available, $514.05.

Illinois, University of, Urbana, Ill.

ASSOCIATION OF MANUFACTURERS OF CHILLED CAR WHEELS FUND. Established, 1916. Annually available, $3,529.

DIVISION OF APPLIED CHEMISTRY TESTING WORK FUND, for research in chemistry. Annually available, $5,516.

FATIGUE OF METALS FUND. Established, 1919. Annually available, $12,000.

GENERAL FUND APPROPRIATION FOR ASTRONOMICAL RESEARCH. Annually available, $3,000.

GRADUATE SCHOOL APPROPRIATION, for general research. Annually available, $25,000.

NATIONAL WARM AIR HEATING AND VENTILATING ASSOCIATION FUND, for investigation of warm air furnaces. Established, 1918. Annually available, $5,901.

U. S. INTERDEPARTMENTAL SOCIAL HYGIENE FUND, for research in social hygiene. Established, 1920. Annually available, $3,500.

Indiana, University of, Bloomington, Ind.

GENERAL FUND APPROPRIATION, for research in physical and biological sciences. Annually available, $10,000.

WATERMAN INSTITUTE FOR SCIENTIFIC RESEARCH FUND. Established, 1915. Original fund, $100,000. Present fund, $102,500. Annually available, $5,000.

Iowa, University of, Iowa City, Iowa.

FUND OF $20,000, for an emergency fund for research projects.

W. C. T. U. FUND, for use in connection with the Welfare Research Station fund. Established, 1920. Annually available, $10,000 for a period of five years.

WELFARE RESEARCH STATION FUND, for the investigation of best scientific methods of conserving and developing the normal child, the dissemination of such knowledge, and the training of students for work in such fields. Established, 1917. Annually available, $25,000.

Johns Hopkins University, Baltimore, Md.

DEPARTMENTAL FUNDS FOR RESEARCH, appropriated in each department of the University.

EPILEPSY RESEARCH FUND, for research in epilepsy. Present fund, $110,000. (A remainder interest in four legacies of $10,000 each will be added to this fund on the death of the life tenants.) Annually available, $5,500.

HERTER LECTURESHIP, for the promotion of a more intimate knowledge of the researches of foreign investigators in the realm of medical science. Established, 1902. Original fund, $25,000. Annually available, $1,000.

JOSEPH DE LAMAR FUND, for study and teaching of the cause and origin of disease and its prevention, and for the study and teaching of dietetics. Established, 1920. Original fund, $2,000,000. Annually available, $100,000.

KENNETH DOWS TUBERCULOSIS RESEARCH FUND, for research in this disease. Established, 1916. Annually available, $17,500.

LINTON FUND, for assisting investigation in anatomy, physiology, pharmacology, and physiological chemistry. Established, 1919. Original fund, $5,000. Annually available, $230.

PHYSIOLOGICAL RESEARCH FUND. Established, 1917. Original fund, $10,000. Annually available, $500.

UNITED STATES INTERDEPARTMENTAL SOCIAL HYGIENE BOARD FUND, for research in social hygiene. Original fund, $19,050. Appropriation for 1920–21 only.

WILLIAM H. WELCH ENDOWMENT FUND, for clinical education and research in medicine, surgery, and pediatrics. Established, 1914. Original fund, $1,273,000. Present fund, $1,623,000. Annually available, $83,000.

Kansas, University of, Lawrence, Kan.

APPROPRIATION for research in biological sciences. Available for 1920–21, $4,757.10.

APPROPRIATION for research in physical sciences. Available for 1920–21, $6,510.

APPROPRIATION for research in mental sciences. Available for 1920–21, $425.

FUND FOR RESEARCH. Annually available, $2,000.

FUND FOR ENGINEERING RESEARCH. Present fund, $1,900.

Kansas State Agricultural College, Manhattan, Kan.

GENERAL FUND, for research on contagious abortion. Annually available, $5,000.

Leland Stanford Junior University, Stanford, Calif.

COFFIN RESEARCH FUND, for study of tropical diseases. Established, 1912. Present fund, $400.

FOOD RESEARCH INSTITUTE, for the intensive study of the problems of production, distribution and consumption of food. Established, 1921. Present fund $700,000. (Provided by Carnegie Corporation for support of the Institute for ten years.)

FUND FOR RESEARCH. Annually available, $2,000.

SUM GIVEN BY OLIVE GROWERS AND THE CANNING INDUSTRY FUND, for study of botulism in California. Established, 1920. Present fund, $12,600.

UNITED STATES INTERDEPARTMENTAL SOCIAL HYGIENE BOARD FUND, for research in social diseases. Established, 1918. Present fund, $7,200. Available, 1920–21, $885.

Massachusetts Institute of Technology, Boston, Mass.

DALTON FUND, for payment of fees for research in textile chemistry. Present fund, $55,000. Annually available, $250.

ELLEN H. RICHARDS FUND, for research in chemistry. Present fund, $15,000. Annually available, $600.

GENERAL BUDGET APPROPRIATION, for research in all departments. Annually available, estimated over $100,000.

HENRY SALTONSTALL FUND, for research. Present fund, $10,000. Annually available, $450.

JAMES SAVAGE FUND, for research. Present fund, $12,500. Annually available, $600.

RICHARD LEE RUSSELL FUND, for research in civil engineering. Present fund, $2,400. Annually available, $80.00.

SUSAN H. SWEET FUND, for research. Present fund, $10,000. Annually available, $450.

WHITNEY FUND, for research in seismology. Present fund, $40,000. Accumulating.

Miami University, Oxford, Ohio.

FUND FOR RESEARCH. Annually available, $800.

Minnesota, University of, Minneapolis, Minn.

ANNUAL BUDGET APPROPRIATION, for research and publication. Annually available, $14,420.

MAYO FOUNDATION, for medical research. Established, 1918. Original fund, $1,693,000.

Northwestern University, Evanston, Ill.

ANNUAL APPROPRIATION TO DEARBORN OBSERVATORY, one-half to be used for research in astronomy. Annually available, $2,500.

CHICAGO ASTRONOMICAL SOCIETY RESEARCH FUND, for research in astronomy. Original fund, $1,500. Present fund, $1,500. Annually available, $75.

DENTAL RESEARCH FUND, for dental research in the University. Original fund, $705.88. Annually available, $35.

JAMES A. PATTEN FUND, for medical research in bacteriology and tuberculosis. Established, 1911. Present fund, $215,750. Annually available, $10,000.

MEDICAL SCHOOL ALUMNI FUND, for medical research. Established, 1904. Original fund, $2,200. Annually available, $110.

NORMAN W. HARRIS LECTURES, to be used to stimulate scientific research of the highest type and to bring the result of such research before the students and friends of the University. Established, 1906. Annually available, $550–$600.

REA BEQUEST, for medical research. Established, 1902. Original fund, $9,700. Annually available, $485.

U. S. INTERDEPARTMENTAL SOCIAL HYGIENE BOARD FUND, for research in chemistry department for compounds of therapeutic value in the treatment of venereal diseases. Established, 1920. Present fund, $5,000, for 1920–21 only.

Pennsylvania, University of, Philadelphia, Pa.

HENRY PHIPPS INSTITUTE FUND, for research in tuberculosis. Established, 1920. Present fund, $500,000. (This endowment is given on conditions that a total of $3,000,000 is raised.)

WISTAR INSTITUTE OF ANATOMY AND BIOLOGY FUND, for research in these two subjects. Established, 1892.

Phillips Academy, Andover, Mass.

ROBERT SINGLETON PEABODY FUND, for American archaeological research in the museum, for exploration and publication. Established, 1901. Original fund, $150,000. Present fund, $458,214.96. Annually available, $21,122.74.

Pittsburgh, University of, Pittsburgh, Pa.

ANNUAL INCOME OF ALLEGHENY OBSERVATORY, for research in astronomy. Annually available, $13,500.

Princeton University, Princeton, N. J.

APPROPRIATIONS TO SCIENTIFIC DEPARTMENTS, for research in the departments. Annually available, $21,200.

Rensselaer Polytechnic Institute, Troy, N. Y.

GENERAL BUDGET APPROPRIATION, for research in all departments. Annually available, $2,000 (as much as is asked by professors, but not generally more than this.)

L. E. LAFLIN FUND, for purchase of materials and apparatus used in original research in the laboratories of the institution. Established, 1914. Original fund, $10,000. Annually available, $500.

RESEARCH FUND, for general research. Established, 1917. Original fund, $11,000 Annually available, $550.

Tulane University, New Orleans, La.

ANNUAL APPROPRIATION, for medical research. Annually available, $1,000.

GENERAL FUND, for research in psychology. Annually available, $3,250.

Utah, University of, Salt Lake City, Utah.

GENERAL FUND APPROPRIATION FOR RESEARCH IN ARCHAEOLOGY. Annually available, $2,000.

GENERAL FUND APPROPRIATION FOR RESEARCH IN METALLURGY. Annually available, $12,500.

Vassar College, Poughkeepsie, N. Y.

RESEARCH FUND OF VASSAR COLLEGE OBSERVATORY, for research only in astronomy. Established, 1910. Original fund, $2,000. Present fund, $2,000. Annually available, $100.

Virginia, University of, Charlottesville, Va.

ANNUAL FUND IN THE LEANDER MCCORMICK OBSERVATORY, for research in astronomy.

GRANT FROM HODGKINS FUND OF THE SMITHSONIAN INSTITUTION, for research in physics. Available for 1920, $200.

Wesleyan University, Middletown, Conn.

AMOS JAY GIVEN BIOLOGICAL FUND, for the maintenance of the department of biology, and for the promotion of research in that subject. Established, 1912. Original funds, $25,000. Annually available, $1,250.

CRAWFORD MEMORIAL FUND, for the purchase of apparatus, and the promotion of research in physics. Established, 1906. Original fund, $5,000. Annually available, $300.

Western Reserve University, Cleveland, Ohio.

APPARATUS FUND, for the purchase of apparatus in medical research. Established, 1908. Present fund, $17,985. Annually available, $1,111.

CRILE PAYNE FUND, for medical research in the Cushing Laboratory of Experimental Medicine. Established, 1909. Present fund, $8,942. Annually available, $534.

Wisconsin, University of, Madison, Wis.

GENERAL ANNUAL APPROPRIATION TO COLLEGE OF ENGINEERING, for research in engineering. Annually available, $3,000.

H. J. HEINZ COMPANY AND NATIONAL PICKLE PACKERS ASSOCIATION FUND, for work on pickle diseases, to be known as "Cucurbit Disease Research Fund." Established 1919. Annually available, $1,000.

NATIONAL TUBERCULOSIS ASSOCIATION FUND, for research work on tuberculosis. Annually available, $200.

NEWPORT COMPANY FUND, for research in synthetic new remedies. Available for 1920, $1,000.

PHARMACEUTICAL EXPERIMENT STATION, for experiments in medicinal plants and vegetable drugs. Established, 1913. Annually available, $5500.

UNITED STATES INTERDEPARTMENTAL SOCIAL HYGIENE BOARD FUND, for research on venereal diseases. Established, 1919. Available for 1920, $12,000.

UNIVERSITY RESEARCH FUND, for special investigations. Established, 1919. Available in 1920, $23,000.

W. A. CLARK, JR., FUND, for purchase of heavy crushing machinery with accessory equipment for experimental work in structural geology. Original fund, $4,000.

WISCONSIN PHARMACEUTICAL RESEARCH FUND, of which half is to be used for research in pharmacy and half to augment the principal. Established, 1917. Original fund, $1,000. Annually available, $500 plus.

Yale University, New Haven, Conn.

CONTRACT WITH ORDNANCE DIVISION OF WAR DEPARTMENT, for experimental work on explosives. For 1920–21, $10,000.

DANA FUND, for original investigation in geology. Original fund, $24,000.

FRANCIS E. LOOMIS FUND, for research in the departments of anatomy, physiology and pharmacology. Established, 1911. Present fund, $20,000 (1916). Annually available, $960.

HADLEY UNIVERSITY FUND, for research in general. Original fund, $1,030. Annually available, $48.

HENRY T. AND WILLIAM D. SLOANE FUNDS, for the study of physics and for research assistants in the New Sloane Laboratory. Established, 1919. Present fund, $125,000.

HEPSA ELI SILLIMAN FUND, a certain extent of which is applicable to scientific research. Established, 1901. Original fund, $94,741.

LOOMIS FUND, for research in astronomy. Established, 1889. Original fund, $312,415. Present fund, $313,865. Annually available, $15,000.

ORGANIC CHEMISTRY RESEARCH FUND, for research in this subject. Established, 1918. Original fund, $600.

RUSSELL H. CHITTENDEN FUND, for research in physiological chemistry. established, 1915. Original fund, $4,000. Annually available, $192.

THOMAS C. SLOANE FUND, for the study of physics in the Sloane Physical Laboratory. Established, 1891. Present fund, $90,000.

V. FELLOWSHIPS AND SCHOLARSHIPS FOR RESEARCH

A. Academies, Associations, Societies and Museums; B. Foundations Hospitals and Research Institutes; C. Universities and Colleges.

A—ACADEMIES, ASSOCIATIONS, SOCIETIES AND MUSEUMS

American Field Service Fellowships for French Universities, 576 Fifth Ave., New York City. (Formerly Society for American Fellowships in French Universities).

FELLOWSHIPS (30), for advanced study and research in French Universities. Established, 1917. Annually available, $1,000 each.

Bernice Pauahi Bishop Museum of Polynesian Ethnology and Natural History, Honolulu, Hawaii.

FELLOWSHIPS (2), for research in anthropology, botany, zoölogy, geology or geography. Established, 1920. Annually available, $1,000 each.

Brooklyn Institute of Arts and Sciences, Brooklyn, N. Y.

TEMPLE PRIME SCHOLARSHIP, for biological research work in the Biological Laboratory at Cold Spring Harbor, L. I. Established, 1919. Annually available, $100.

Chemists' Club of New York, 50 East 41st St., New York City.

BLOEDE SCHOLARSHIP, for research in industrial chemistry and engineering. Established, 1916. Original fund, $10,000. Present fund, $10,000. Annually available, $500.00.

HOFFMAN SCHOLARSHIP, for research in industrial chemistry and engineering. Established, 1916. Original fund, $10,000. Present fund, $10,000. Annually available, $500.00.

Gypsum Industries Association, H. H. Macdonald, Secretary, 7647 Greenview Avenue, Chicago, Ill.
FELLOWSHIPS (6) for investigation of the use of gypsum in crop production. Annually available, $1,000–$1500.

B—FOUNDATIONS, HOSPITALS AND RESEARCH INSTITUTES

American Scandinavian Foundation, 25 West 45th St., New York City.
TRAVELING FELLOWSHIPS (20) OF $1,000 EACH, five for travel and study in Denmark, 10 in Sweden and 5 in Norway, for the purpose of drawing the American and Scandinavian peoples closer in bonds of intellectual kinship. Established, 1911. Original fund, $500,000. Present fund, $565,082.48. Annually available, $40,000. (Only one-half available for United States.)

Marine Biological Laboratory, Woods Hole, Mass.
LUCRETIA CROCKER SCHOLARSHIPS IN BIOLOGICAL RESEARCH, for teachers in Boston. Annually available, $50.

SCHOLARSHIP OF $100, for rent of research room or table at the Marine Biological Laboratory, Woods Hole, Mass. Established, 1898. Annually available, $100.

National Research Council, 1701 Mass. Ave., Washington, D. C.
FELLOWSHIPS, for research in physics and chemistry. Supported by the Rockefeller Foundation. Established, 1920. Present fund, $500,000. Annually available, $100,000.

Research Corporation, 31 West 43rd St., New York City.
FELLOWSHIP, for scientific investigation. Established, 1917.

Trudeau Foundation, Saranac, N. Y.
FELLOWSHIPS, for research in tuberculosis.

C—UNIVERSITIES AND COLLEGES

Amherst College, Amherst, Mass.
RUFUS B. KELLOG UNIVERSITY FELLOWSHIP, for study and research. Original fund, $30,000. Septennially available, $2,000.

Arizona, University of, Tucson, Arizona.
BUREAU OF MINES FELLOWSHIPS (2), for research in mining, metallurgy or geology in coöperation with the U. S. Bureau of Mines. Established, 1916. Annually available, $750 each.

Brown University, Providence, R. I.

Arnold Biological Fellowship, for research in biology. Original fund, $10,000. Annually available, $500.

E. I. du Pont de Nemours and Company Fellowship for Research in Chemistry. Annually available, $750.

Emma Josephine Ayer Arnold Archaeological Fellowship, for research in archaeology. Original fund, $10,000. Annually available, $500.

Morgan Edwards Fellowship, for original research in any department of knowledge. Original fund, $10,000. Biennially available, $1,000.

Bryn Mawr College, Bryn Mawr, Pa.

Helen Schaeffer Huff Memorial Research Fellowship, for research in either physics or chemistry. Established, 1913. Annually available, $1,200.

Mary E. Garrett European Fellowship, for study and research in a European university. Established, 1894. Annually available, $500.

President M. Carey Thomas Fellowship, for study and research in a European university. Established, 1896. Annually available, $500.

Research Fellowship, for research in chemistry. Established, 1907. Annually available, $530.

Resident Research Fellowship, for research in archaeology. Established, 1909. Annually available, $530.

Resident Research Fellowship, for research in biology. Established, 1885. Annually available, $530.

Resident Research Fellowship, for research in chemistry. Established, 1893. Annually available, $530.

Resident Research Fellowship, for research in geology. Established, 1912. Annually available, $530.

Resident Research Fellowship, for research in mathematics. Established, 1885. Annually available, $530.

Resident Research Fellowship, for research in physics. Established, 1896. Annually available, $530.

Resident Research Fellowship, for research in psychology. Established, 1915. Annually available, $530.

Resident Research Fellowship, for research in psychology. Established, 1896. Annually available, $530.

California Institute of Technology, Pasadena, Calif.

Teaching Fellowships in Chemistry (6), for teaching, study and research in chemistry. Established, 1917 and 1919. Annually available, $750 each.

Fellowships (3) for physical and chemical research. Established, 1916. Annually available, $1,000 each.

California, University of, Berkeley, Calif.

E. I. du Pont de Nemours and Company Fellowships (2), for research in chemistry. Annually available, $750.

James Rosenberg Memorial Scholarship, for research in agriculture. Annually available, $600.

James W. Geowey Scholarship, for research in natural science. Established, 1904. Annually available, $600.

John W. McKay, Jr., Fellowships (2), for research in electrical engineering at the University of California. Annually available, $600 each.

LeConte Memorial Fellowship, for research and study either at the University of California or elsewhere. Annually available, $750.

Lick Observatory Fellowships (3), for research in astronomy at Lick Observatory. Annually available, $600 each.

Martin Kellogg Fellowship, for research in astronomy in the Lick Observatory. Annually available, $1,200.

University Fellowships (8), for research in a chosen subject. Annually available, $500 each.

Whiting Fellowships (2), for research in physics either here or abroad Established, 1895. Original fund, $20,000. Present fund, $26,350. Annually available, $600 each.

Carnegie Institute of Technology, Pittsburgh, Pa.

Bureau of Personnel Research Fellowships (4 or more $300 to $600 each, 4 research positions $1,500 to $6,000 each), to stimulate research in the application of psychology to personnel problems of business and industry and to train men and women in applied psychology. Established, 1916. Original fund, $15,000. Present fund, $22,000. Annually available, $15,000 for five years.

Case School of Applied Science, Cleveland, Ohio.

Drury Fellowships (6), for engineering study. Established, 1917. Annually available, $500 each.

Industrial Fellowships, for investigation of a scientific or technical subject which may be of interest to a manufacturer giving a fellowship.

Wallace Clement Sabine Research Fellowship in Acoustics, to encourage investigation in acoustics. Established, 1919. Annually available, $1,000.

Chicago, University of, Chicago, Ill.

E. I. du Pont de Nemours and Company Fellowship, for research in chemistry. Established, 1918. Annually available, $750.

Edith Barnard Memorial Fellowship, for research in chemistry. Established, 1915. Present fund, $3,000. Annually available, $156.

GUSTAVUS F. SWIFT FELLOWSHIP, for research in chemistry. Established, 1908. Present fund, $17,809. Annually available, $920.

GYPSUM INDUSTRIAL ASSOCIATION RESEARCH FELLOWSHIPS (2), for investigations of value of gypsum and other sulphur compounds as fertilizers. Established, 1919. Annually available, $750.

HOME ECONOMICS FELLOWSHIP, for research in nutrition or related fields. Established, 1919. Annually available, $600.

HOSKINS FELLOWSHIP, for research in chemistry. Established, 1919. Annually available, $400.

JOSEPH LOEWENTHAL FELLOWSHIP, for research in chemistry. Established, 1900. Present fund, $10,000. Annually available, $400.

LOGAN RESEARCH FELLOWSHIPS (2), one for research in bacteriology, one in medicine. Established, 1917. Present fund, $52,500. Annually available, $3,000.

UNIVERSITY FELLOWSHIPS, to encourage research in any department of the University. Present fund, $21,100. Annually available, $120 to $520 each.

Cincinnati, University of, Cincinnati, Ohio.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

Columbia University, New York City.

ABRAM DUBOIS MEMORIAL FELLOWSHIP, for research in the diseases of the eye. Restricted to graduates of the College of Physicians and Surgeons. Established, 1910. Present fund, $18,000. Annually available, $900.

BARNARD FELLOWSHIP, for research in physical science at Columbia or elsewhere. Established, 1889. Present fund, $10,000. Triennially available, $1,350.

BLUMENTHAL FELLOWSHIP, for research in medicine and surgery. Established, 1909. Annually available, $1,000.

CAROLINE DUROR MEMORIAL GRADUATE FELLOWSHIP, for graduate showing most distinction in her chosen line. Established, 1912. Annually available, $600.

CLARK SCHOLARSHIP, for promoting the discovery of new facts in medical science. Established, 1894. Present fund, $14,932.75. Annually available, $672.

COOLIDGE FELLOWSHIPS (2), for research in medicine. Established, 1918. Original fund, $2,500. Annually available, $1,250 each.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

ERNEST KEMPTON ADAMS RESEARCH FELLOWSHIP, for research in the physical sciences, or in their practical applications, at Columbia or elsewhere. Established, 1904. Present fund, $50,000. Annually available, $1,250.

GOLDSCHMIDT FELLOWSHIP, for research in chemistry. Established, 1908. Present fund, $16,350. Annually available, $736.47 (1920–21).

GOTTSBERGER FELLOWSHIP, for graduate students desiring to pursue their studies abroad. Awarded biennially.

MARIA MCLEAN PROUDFIT FELLOWSHIP, for advanced studies in internal medicine. Established, 1899. Quadrennially available, $1,237.50.

NATIONAL BISCUIT COMPANY FELLOWSHIP, for industrial research. Established, 1918. Original fund, $2,400.

PLAUT FELLOWSHIP, for research in pharmacy abroad. Established, 1915. Annually available, $500.

SAMUEL FRANKLIN EMMONS MEMORIAL FELLOWSHIP, for research in economic geology. Established, 1913. Present fund, $13,923.27. Annually available, $626.54 (1920–21).

SAMUEL WILLARD BRIDGAM FELLOWSHIP, for research in applied science. Established, 1915. Present fund, $21,000. Annually available, $983.25.

TROWBRIDGE FELLOWSHIP, for research in engineering. Established, 1893. Present fund, $10,000. Annually available, $500.

TYNDALL FELLOWSHIP, for research in physics. Established, 1885. Original fund, $10,945. Triennially available, $972.

UNIVERSITY FELLOWSHIPS (12), for study and original investigation. Established, 1891. Annually available, $750 each.

WILLIAM BAYARD CUTTING TRAVELING FELLOWSHIPS, for graduate students who have given evidence of ability to make contribution of value to letters, science, law, medicine or fine arts. Annually available, $1,000. Open to men who have been graduate students for one academic year, and to graduates of the University. May be held in the United States or abroad.

WILLIAM MITCHELL FELLOWSHIP, for research in letters and science at Columbia or elsewhere. Established, 1908. Present fund, $10,000. Annually available, $450.

Cornell University, Ithaca, N. Y.

CHARLES BULL EARLE MEMORIAL FELLOWSHIP, for research in mechanical and electrical engineering. Established, 1920. Present amount, $10,000. Annual amount available, $500.

CHARLES L. SHELDON FELLOWSHIPS, for research in clinical medicine. Established, 1912. Annually available, $200 each.

E. I. DU PONT DE NEMOURS FELLOWSHIP, for research in chemistry. Established, 1919. Annually available, $750.

EDGAR J. MEYER MEMORIAL FELLOWSHIP, for research in engineering. Established, 1913. Present fund, $10,000. Annually available, $541.

ELON H. HOOKER FELLOWSHIP, for research in hydraulic engineering. Established, 1919. Original fund, $8,500. Annually available, $400.

GRASSELLI FELLOWSHIP, for research in chemistry. Established, 1920. Annually available, $750.

J. METCALF POLK FELLOWSHIP, for research in pathology. Established, 1919. Annually available, $250.

SEVEN INDUSTRIAL FELLOWSHIPS, for research in agricultural subjects. Annually available, $1,000 each.

SIMON HENRY GAGE FELLOWSHIP, for research in animal biology. Established, 1916. Present fund, $3,435. Annually available, $176.

There are several fellowships at Cornell which are not strictly for research, but any of which may be devoted to investigation or research.

Harvard University, Cambridge, Mass.

ARTHUR TRACY CABOT FELLOWSHIP, for the advancement of surgery in this country or elsewhere. Established, 1913. Original fund, $25,000. Annually available, $800.

BULLARD FELLOWSHIPS (3), for original investigation in medical science. Established, 1891. Original fund, $15,000. Annually available, $275 (2), $300 (1).

CENTRAL AMERICAN ARCHAEOLOGY FELLOWSHIP, for research in archaeology. Established, 1907. Unrestricted. Annually available, $650.

CHRISTOPHER WELD FELLOWSHIP, for research in any subject. Restricted to Harvard students. Annually available, $550.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

EDWARD AUSTIN FELLOWSHIPS (4), for research in any subject. Restricted to residents of Cambridge. Annually available, $550 each.

EDWARD HICKLING BRADFORD FELLOWSHIP, for medical research. Established, 1918. Original fund, $25,000. Annually available, $1,125.

EDWARD HOPPER FELLOWSHIP, for research in any subject. Unrestricted. Annually available, $1,200.

EDWARD C. PICKERING FELLOWSHIP FOR WOMEN, in astronomy. Annually available, $459.22.

FRANCIS PARKMAN FELLOWSHIP, for research in any subject. Unrestricted. Annually available, $500.

FREDERICK SHELDON FUND FOR TRAVELING FELLOWSHIPS, for further study or investigation, in this country or abroad. Restricted to Harvard students. Established, 1909. Original fund, $346,458.70. Present fund, $438,746. Annually available, $21,595.

George H. Emerson Scholarships, for research in zoölogy, geology, mineralogy and chemistry. Established, 1903. Original fund, $20,656.20. Present fund, $37,761.17. Annually available, $400 each.

Harris Fellowship, for research in science (not medicine). Restricted to Harvard graduates residing in Cambridge. Established, 1868. Annually available, $550.

Harvard Fellowship in the International School of American Archaeology and Ethnology, Mexico City. Established, 1911. Annually available, $650.

Hemenway Fellowship, for study of American archaeology and ethnology. Restricted to Harvard students. Established, 1891. Original fund, $10,000. Present fund, $13,488.98. Annually available, $625.

Henry P. Walcott Fellowship, for clinical research and teaching. Established, 1910. Annually available, $1,200.

Humboldt Scholarship, for the study of zoölogy. Unrestricted. Established, 1869. Present fund, $8,917.57. Annually available, $437.03.

James Jackson Cabot Fellowship, for aid and encouragement to practical work in scientific medicine. Established, 1906. Original fund, $6,000. Present fund, $13,100. Annually available, $638.

John Kirkland Fellowship, for research in any subject. Restricted to Harvard students. Annually available, $500.

John Tyndall Scholarship, for research in physics. Unrestricted. Established, 1885. Original fund, $10,800. Present fund, $14,184. Annually available, $625.

John White Browne Scholarship, for research in medicine. Established, 1918. Annually available, $900.

Maria Mitchell Fellowship, for research in astronomy. Annually available, $581.33.

Parker Fellowships (4), for research in any science. Restricted to Harvard students. Annually available, $750 each.

Philip H. Sears Fellowship, for research in psychology. Established, 1914. Annually available, $750.

Princeton Fellowship, for research in any subject. Restricted to Princeton graduate. Annually available, $500.

Thaw Fellowship, for research relating to the Indian race of America or other ethnological and archaeological investigations. Established, 1890. Present fund, $30,202.92. Annually available, $1,204.

Virginia Barret Gibbs Scholarship, for research in zoölogy. Established, 1892. Present fund, $7,168.77. Annually available, $349.18.

Whiting Fellowships (4), for research in physics. Established, 1895. Original fund, $20,000. Annually available, $350.

WILLIAM WATSON GOODWIN FELLOWSHIP, for research in archaeology. Established, 1915. Original fund, $17,520. Annually available, $650.

WINTHROP SCHOLARSHIP, for the study of archaeology and ethnology. Established, 1895. Original fund, $5,000. Present fund, $7,422.50. Annually available, $325.

Hawaii, University of, Honolulu, Hawaii.

HAWAIIAN PINEAPPLE PACKERS' ASSOCIATION FELLOWSHIP, for research in problems connected with the growing of pineapples. Established, 1920. Annually available, $1,200 for three years.

TEACHING FELLOWSHIP, for research work in either botany or zoölogy. Established, 1920. Annually available, $750.

Idaho, University of, Moscow, Idaho.

UNITED STATES BUREAU OF MINES FELLOWSHIP (2–4), for research in mining under direction of the Bureau of Mines. Established, 1917. Annually available, $900 each.

Illinois, University of, Urbana, Ill.

CARR FELLOWSHIP, for research in chemistry. Established, 1919. Original fund, $10,000. Present fund, $10,000.

CORNING GLASS WORKS FELLOWSHIP, for research in chemistry. Established, 1920. Original fund, $800. Annually available, $800.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, in chemistry. Present fund, $15,000. Annually available, $750.

GRADUATE RESEARCH ASSISTANTSHIPS (14), for research in problems of special importance to engineering, to manufacturing, railroad, mining and industrial interests and stimulation and elevation of engineering education. Annually available, $500 each.

UNITED STATES BUREAU OF MINES FELLOWSHIP, for research in mining under the direction of the Bureau of Mines.

Indiana, University of, Bloomington, Ind.

LAWRENCE FELLOWSHIP, for research in astronomy. Annually available, $600 plus traveling expenses to the Observatory at Flagstaff, Arizona, plus furnished room at Observatory.

SPECIAL FELLOWSHIPS (3), for men of exceptional ability and merit who may or may not have the Ph.D. degree. Annually available, $1,000 to $1,500.

UNIVERSITY FELLOWSHIPS, for research in any department of the University. Annually available, $300–$500.

Iowa State College of Agriculture and Mechanic Arts, Ames, Iowa.

GRADUATE FELLOWSHIPS AND SCHOLARSHIPS, to promote graduate study and research. Annually available, scholarships, $200, teaching fellowships, $400, junior research fellowships, $300, senior research fellowship, $500.

RESEARCH FELLOWSHIPS, for research in American agricultural history, with special reference to its economic phases. Annually available, $400.

SPECIAL RESEARCH AND INDUSTRIAL FELLOWSHIP, for study of special industrial problems.

TEACHING AND RESEARCH FELLOWSHIPS AND SCHOLARSHIPS, for research in the department of agriculture. Annually available, $200–$500 each.

Iowa, University of, Iowa City, Iowa.

NO FIXED FELLOWSHIPS, but given for research in any desired field, preference given to large projects. Present fund, about $48,000. Annually available, research associate, $800 up, research assistant, $500 up, senior fellow, 4 at $600, junior fellow, 2 at $300.

WELFARE RESEARCH STATION, a limited number of half time research assistantships are given, and one or two temporary appointments of larger salary. Annually available, $600 to $1,000.

Johns Hopkins University, Baltimore, Md.

BRUCE FELLOWSHIP, for research in biology. Established, 1887. Original fund, $10,000. Annually available, $450.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIPS (2), for research in chemistry. Established, 1918. Original fund, $1,500. Annually available, $750.

GEORGE HUNTINGTON WILLIAMS MEMORIAL FELLOWSHIP, for research in geology. Established, 1916. Original fund, $10,000. Annually available, $500.

GRAFFLIN SCHOLARSHIPS, for research in industrial chemistry. Established, 1915. Annually available, $1,000.

JOHNSTON FELLOWSHIPS (3), for research in a chosen subject. Established, 1904. Original fund, $90,000. Annually available, $1,200.

RESEARCH FELLOWSHIPS (6), for investigation in hygiene and public health. Established, 1916. Annually available, $6,000.

Kansas State Agricultural College, Manhattan, Kansas.

FELLOWSHIPS, for research in agronomy, animal husbandry, dairy husbandry, poultry husbandry, food economy and nutrition, bacteriology, botany. Annually available, $450 each.

FELLOWSHIPS (2), for research in engineering. Annually available, $400 each.

KANSAS FLOUR MILLS COMPANY FELLOWSHIP, to advanced students specializing in the milling industry. Annually available, $300.

Lafayette College, Easton, Pa.

EDWARD HART FELLOWSHIP, for research work on problems connected with viscous and plastic flow. Restricted to students in chemistry holding bachelor's degree. Established, 1919. Original fund, $10,000. Annually available, $500.

Lehigh University, Bethlehem, Pa.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

Leland Stanford Jr. University, Stanford, Calif.

BUCKEL FELLOWSHIP, for the study of backward and feeble-minded children. Established, 1914. Annually available, $1,000 ($500 from Buckel estate and $500 from the University).

SPERRY FLOUR INVESTIGATIONS FELLOWSHIP. Established, 1919. Annually available, $750.

TEACHING FELLOWSHIPS, for research in chemistry (2). Established, 1917. Annually available, $600 each.

THOMAS WELTON STANFORD FELLOWSHIP, for psychical research. Annually available, $2,000.

UNIVERSITY FELLOWSHIPS (8), for research in any subject. Established, 1920. Annually available, $750 each.

Maryland, University of, College Park, Md.

UNIVERSITY FELLOWSHIPS, for study and research. Annually available, $500–$720.

Massachusetts Institute of Technology, Cambridge, Mass.

AUSTIN RESEARCH FELLOWSHIPS (2), for research in a chosen subject. Annually available, $500 and tuition for each.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

MALCOLM COTTON BROWN FELLOWSHIP, for study of physics. Present fund, $10,000. Annually available, $500.

MOORE SCHOLARSHIP FUND, for study of organic chemistry in Europe. Awarded from time to time. Annually available when awarded, $250.

Mellon Institute, Pittsburgh, Pa.

INDUSTRIAL FELLOWSHIPS (1919–1920, 47), for research in industrial problems. Established, 1911. Original fund, $39,700. Present fund, $293,680.

Michigan, University of, Ann Arbor, Michigan.

ACME WHITE LEAD AND COLOR WORKS FELLOWSHIP IN PAINT AND VARNISH MANUFACTURE, for the study of problems connected with the manufacture of paints and varnishes. Established, 1911. Annually available, $750.

BRAUN FELLOWSHIP, for research in any subject. Unrestricted. Annually available, $500.

Cole Fellowship, for research in botany. Restricted to Michigan graduates. Annually available, $600.

Detroit Edison Company Fellowship, for investigation of approved subjects relative to moderate cost of country roads. Established, 1915. Annually available, $300.

E. I. du Pont de Nemours and Company Fellowship, for research in chemistry. Annually available, $750.

Frederick Stearns and Company Fellowship, for research in pharmacy. Annually available, $500.

National Aniline and Chemical Company Fellowships (2), for research in chemistry. Annually available, $750 each.

Roy D. Chapin Fellowships (2), for research in highway engineering, particularly directed towards the state of road surfaces. Established, 1916. Annually available, $300.

United States Rubber Plantations Incorporated Fellowship, for research in rubber produce. Annually available, $1,200.

University Fellowships (15), for research in any subject. Unrestricted. Annually available, $300 (10), $500 (5).

Whittier Fellowship, for research in botany. Unrestricted. Annually available, $200.

Ric-wil Fellowship, for research in heat transmission. Annually available, $600.

Minnesota, University of, Minneapolis, Minn.

Shevlin Fellowships (4), for research in agriculture (1), chemistry (1), medicine (1), and one in any subject. Annually available, $500 each.

E. I. du Pont de Nemours and Company Fellowship, for research in chemistry. Annually available, $750.

New York University, New York City.

Christian A. Herter Research Fellowship, for research in chemical pathology, physiological chemistry or pharmacology. Established, 1903. Original fund, $6,000. Annually available, $300.

Samuel Browne Duryea Fellowship, for research in engineering. Established, 1895. Original fund, $4,350. Annually available, $200.

William A. Inman Fellowship, for research in science. Established, 1890. Original fund, $5,000. Annually available, $200.

North Carolina, University of, Chapel Hill, N. C.

E. I. du Pont de Nemours and Company Fellowship, for research in chemistry. Annually available, $750.

North Dakota University, University, N. D.

Graduate Fellowships (3), for original research in any department of the University. Annually available, $300.

INDUSTRIAL FELLOWSHIP, for research in solution of problems connected with the development of the resources and industries of the state. Annually available, $400.

Northwestern University, Evanston, Ill.

GRADUATE SCHOLARSHIPS, for research in any department. Restricted to graduate students. Annually available, $3,600 (10 at $300, 6 at $100).

MARCY SCHOLARSHIP, for research in biology (rent of research table at the Marine Biological Laboratory, Woods Hole, Mass.). Original fund, $1,000. Annually available, $50.

JAMES A. PATTEN FELLOWSHIPS (4), for research in medical science. Restricted to university students. Established, 1910. Original fund, $50,000. Present fund, $50,000. Annually available, $2,000 (4 at $500 each).

Oberlin College, Oberlin, Ohio.

MARY MCKENZIE LINCOLN SCHOLARSHIP, for research table at Marine Biological Laboratory, Woods Hole, Mass. Established, 1917. Original fund, $1,000. Annually available, $40.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

Ohio State University, Columbus, Ohio.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

SCHOLARSHIPS AND FELLOWSHIPS, for graduate study and research. Annually available, Scholarships $250; Fellowships $500.

STILLMAN W. ROBINSON FELLOWSHIP, for the encouragement of graduate research in engineering. Annually available, $500.

Pennsylvania, University of, Philadelphia, Pa.

BENNET FELLOWSHIP, for research in any subject. Restricted to women. Annually available, $225.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

FRAZER FELLOWSHIP, for research in physics. Restricted to resident at University. Annually available, $500.

HARRISON FELLOWSHIPS (8), for research in any subject. Restricted to resident at University. Annually available, $100.

HARRISON FELLOWSHIPS (19), for research in any subject. Annually available, $500.

HARRISON RESEARCH FELLOWSHIPS (5), for research in any subject. Restricted to residents of Philadelphia. Annually available, $800 each.

HENRIETTA HECKSHER FELLOWSHIP, for research in medicine. Established, 1913. Annually available, $500.

MOORE FELLOWSHIPS (2), for research in any subject at University. Annually available, $200 each.

PEPPER FELLOWSHIP, for research in any subject at University. Annually available, $225.

ROBERT M. GIRVIN FELLOWSHIP, for research in medical sciences. Established, 1913. Annually available, $650.

ROBERT ROBINSON PORTER FELLOWSHIP, for research in medical sciences. Established, 1912. Annually available, $600.

SAMUEL DIXON FELLOWSHIP, for research in bacteriology.

THOMAS A. SCOTT FELLOWSHIP, for research in hygiene. Established, 1892. Annually available, $1,000.

TYNDALL FELLOWSHIP, for research in physics. Unrestricted. Annually available, $500.

WISTAR INSTITUTE OF ANATOMY AND BIOLOGY FELLOWSHIPS, for research in anatomy and biology.

WOODWARD FELLOWSHIP, for research in physiological chemistry.

Princeton University, Princeton, N. J.

CHARLOTTE ELIZABETH PROCTOR FELLOWSHIPS, (10) in graduate school. Established, 1912. Original fund, $300,000. Annually available, minimum of $1,000 each.

CLASS OF 1860 EXPERIMENTAL SCIENCE FELLOWSHIP, for research in science. Established, 1870. Original fund, $10,000. Annually available, $600.

CLASS OF 1877 UNIVERSITY.FELLOWSHIP, for research in biology. Established 1904. Annually available, $400.

CLASS OF 1883 UNIVERSITY FELLOWSHIPS (2), for research in the department of politics, physics, chemistry, biology or geology. Established, 1910. Original fund, $30,000. Annually available, $600 each.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

E. M. BIOLOGICAL FELLOWSHIP, for the use of a table in the Laboratory of the U. S. Bureau of Fisheries at Woods Hole, Mass.

FRANCIS HINTON MAULE BIOLOGICAL FELLOWSHIP, for research in biology. Established, 1901. Present fund, $10,000. Annually available, $500.

HARVARD FELLOWSHIP, for research in chemistry. Established, 1905. Original fund, $10,000. Annually available, $500.

J. S. K. MATHEMATICAL FELLOWSHIP, for research in mathematics. Established, 1873. Original fund, $11,000. Present fund, $24,150. Annually available, $1,100.

JAMES W. QUEEN GRADUATE SCHOLARSHIP, for research in physics. Established, 1908. Original fund, $5,000.

ORSON DESAIX MUNN UNIVERSITY FELLOWSHIP, for research in electrical engineering. Established, 1908. Present fund, $10,000.

PORTER OGDEN JACOBUS FELLOWSHIP, for research in any subject desired. Original fund, $25,000. Annually available, $1,000.

SAYRE FELLOWSHIP IN APPLIED ELECTRICITY. Annually available, $600.

THAW FELLOWSHIP, for research in astronomy. Established 1896. Original fund, $10,000. Annually available, $500.

UNIVERSITY FELLOWSHIPS, to encourage advanced study and promote original research in the several departments to which they are assigned. Annually available, approximately $30,000.

Rensselaer Polytechnic Institute, Troy, N. Y.

RUSSELL SAGE, 2d, MEMORIAL FELLOWSHIPS (2). Annually available, $600 each.

Rutgers College, New Brunswick, N. J.

ALDUNATE-BASCUNAN CHILEAN NITRATE RESEARCH FELLOWSHIP, for investigations of the factors which influence the transformation and utilization of nitrate nitrogen in the soil; also study of factors which are responsible for the differences in the recovery of nitrate nitrogen by different crops and under varying seasonal and soil conditions. Established, 1917. Original fund, $2,000. Annually available, $900.

ALFRED H. COWLES FELLOWSHIP, for research on the functions and value of calcium silicate in plant production. Established, 1920. Annually available, $300.

ALPHANO-HUMUS COMPANY FELLOWSHIP, for research on the value of peat and other organic matter as a source of energy for the fixation of nitrogen by azotabacter. Established, 1920. Annually available, $1,200.

AMERICAN CYANAMID FELLOWSHIP, for research on the value of ammonium phosphates as a source of plant-food. Established, 1920. Annually available, $1,800.

AMMONIUM SULPHATE RESEARCH FELLOWSHIP, for research in the value of ammonium sulphate as a source of nitrogen to vegetation; investigations in the availability of nitrogen in ammonium sulphate; function of sulphur in ammonium sulphate; field and pot experiments to determine the changes which this substance undergoes in the soil and the chemical and biological changes produced by its application. Established, 1919. Annually available, $900.

COMMONWEALTH FERTILIZER COMPANY FELLOWSHIP, for research in the value of calcined phosphates as a source of available phosphorus for plant production. Established, 1920. Annually available, $1,500.

INTERNATIONAL SALT COMPANY FELLOWSHIP, to study the possible value of common salt in making available potash and other mineral plant-food in the soil. Established, 1917. Annually available, $600.

LIPMAN FELLOWSHIPS (2), to study problems relating to the place and functions of sulfur in the plant world. Established, 1920. Annually available, $1,200 each.

NEW JERSEY ZINC COMPANY ZINC OXIDE RESEARCH FELLOWSHIP, to study the fungi responsible for the deterioration of paints on the interior walls of greenhouses and other buildings. Established, 1916. Annually available, $1,000.

YARDLEY CHEMICAL CORPORATION FELLOWSHIP, for research on the value of certain disinfectants for controlling animal diseases. Established, 1920. Annually available, $900.

Smith College, Northampton, Mass.

FELLOWSHIPS (6). Restricted to alumnae or member of the Smith college faculty. Annually available, $500 each.

Texas, University of, Austin, Tex.

UNIVERSITY FELLOWSHIPS AND SCHOLARSHIPS (20), to promote higher scholarship and research in the college of arts and graduate department. Established, 1913. Annually available, 5 University fellowships, $200 each; 10 University scholarships, $100 each; 5 University advanced fellowships, $300 each.

Utah, University of, Salt Lake City, Utah.

FELLOWSHIPS, for research in chemistry. Annually available, $2,800.

FELLOWSHIPS, for research in engineering. Annually available, $700.

Vassar College, Poughkeepsie, N. Y.

GRADUATE FELLOWSHIPS (4 non-resident). Unrestricted. Established, 1911. Annually available, $500.

MARY RICHARDSON AND LYDIA PRATT BABBOTT FELLOWSHIP, for study and research. Established, 1895. Annually available, $400.

SUTRO FELLOWSHIPS (2), for graduate study and research. Established, 1914. Original fund, $20,000. Annually available, $500 each.

VASSAR STUDENTS AID SOCIETY FELLOWSHIPS, for graduate study and research. Established, 1905. Original fund, $10,800.

Virginia, University of, Charlottesville, Va.

ADAMS FELLOWSHIP FROM COLUMBIA UNIVERSITY, for research in the determination of stellar parallax by photography in the Leander McCormick Observatory. Annually available, $1,000 for 5 years.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

Washington, State College of, Pullman, Wash.

RESEARCH ASSISTANT, for research in the School of Mines. Annually available, $100 to $750

RESEARCH ASSISTANTS (4), for research in agriculture. Annually available, $100 to $750.

RESEARCH FELLOWSHIP, for research in engineering at the Engineering Experiment Station. Annually available, $100 to $750.

RESEARCH FELLOWSHIPS (2), for research in botany. Annually available, $100 to $750.

Washington, University of, Seattle, Wash.

COLUMBIA UNIVERSITY FELLOWSHIP, for research in mining, engineering and chemistry. Established, 1917. Annually available, $250.

FELLOWSHIPS IN COLLEGE OF MINES, in coöperation with the U. S. Bureau of Mines. Established, 1917. Annually available, $720.

MARS FELLOWSHIP, for research in astronomy. Established, 1917. Annually available, $600.

UNIVERSITY FELLOWSHIPS (3), for research in all departments. Established, 1909. Original fund, $25,000. Annually available, $1,250 each.

Washington University, St. Louis, Mo.

GENERAL SURGICAL FELLOWSHIPS, not definitely established, but with an amount varying with the experience of the applicant. Available, 1920–21, $900.

MEDICAL FELLOWSHIPS (2), for research in medical department. Annually available, $1,000.

RUFUS J. LACKLAND FELLOWSHIPS (5 for research, 2 for teaching), for research and teaching. Restricted to students who show a decided fitness for research. Established, 1909 and 1910. Annually available, $500 each.

SURGICAL FELLOWSHIP, for special neurological work. Established, 1916. Annually available, $1,200.

Wellesley College, Wellesley, Mass.

ALICE FREEMAN PALMER FELLOWSHIP, for study abroad, for study at any American College or University, or privately for independent research. Established, 1903. Annually available, $1,000.

SCHOLARSHIP AT THE ZOÖLOGICAL STATION IN NAPLES, for research in botany, zoölogy or physiology.

Western Reserve University, Cleveland, Ohio.

GEORGE W. CRILE FELLOWSHIP, for medical research in surgery, within or without the University. Established, 1920. Original fund, $100,000. Annually available, $5,000.

HANNA FELLOWSHIP, for medical research. Established, 1909. Present fund, $12,180. Annually available, $594.

Williams College, Williamstown, Mass.

HORACE F. CLARK PRIZE SCHOLARSHIPS, to be awarded for superior scholarship, general ability and interest in scholarly research. Annually available, $1,000 (2 at $500 each or 1 at $1,000).

Wisconsin, University of, Madison, Wis.

A. J. HORLICK SCHOLARSHIP IN AGRICULTURE, for special research on some phase of inheritance of disease resistance in plants. Established, 1915. Annually available, $250.

AMERICAN PHARMACEUTICAL ASSOCIATION SCHOLARSHIP, for research in pharmacy. Annually available, $250.

CUTLER-HAMMER MANUFACTURING COMPANY OF MILWAUKEE FELLOWSHIP, for research in physics. Annually available, $500.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

FRITZSCHE BROTHERS FELLOWSHIP, for research in problems relating to the cultivation of the Monardas, in the distilling of monarda oil and its use in the manufacture of thymol. Established, 1917. Annually available, $500.

HOLLISTER FELLOWSHIP, for research in pharmacy. Restricted to graduate students in the department of pharmacy. Established, 1914. Original fund, $10,328. Annually available, $562.53.

NATIONAL FERTILIZER ASSOCIATION INDUSTRIAL FELLOWSHIP, for research in soils. Established, 1919. Annually available, $2,000 for three years.

SPECIAL FELLOWSHIP OF INSECTICIDE COMPANIES, for research in economic entomology. Annually available, $600.

STUDENT RESEARCH ASSISTANTSHIPS, for research assistants in forest products laboratory. Annually available, $300 each.

UNIVERSITY FELLOWSHIPS, for promoting higher scholarship and research in the several departments. Annually available, $500 each.

WISCONSIN GAS ASSOCIATION INDUSTRIAL FELLOWSHIP, for research in chemical engineering. Annually available, $500.

Yale University, New Haven, Conn.

BISHOP MUSEUM FELLOWSHIPS (2), for research in anthropology, botany, zoölogy, geology or geography. Established, 1920. Annually available, $1,000 each.

DANA FELLOWSHIP, for research in geology. Established, 1912. Annually available, $500.

E. I. DU PONT DE NEMOURS AND COMPANY FELLOWSHIP, for research in chemistry. Annually available, $750.

EATON SCHOLARSHIP, for research in botany. Established, 1897. Original fund, $2,000. Annually available, $195.

Henry Bradford Loomis Fellowship, for research in chemistry. Established, 1905. Original fund, $10,000. Annually available, $465.

Huntington Fellowship, for research in geography. Established, 1920. Annually available, $500.

Ives Fellowship, for research in philosophy and psychology. Established 1908. Original fund, $10,000. Annually available, $465.

John Sloane Fellowship, for research in physics. Established, 1889. Original fund, $10,000. Annually available, $465.

Loomis Fellowship, for research in physics. Established, 1902. Original fund, $10,000. Annually available, $465.

National Aniline and Chemical Company Fellowship. Established, 1920. Annually available, $750.

Page Scholarship, for research in anthropology and the science of society. Established, 1901. Annually available, $500.

Seesel University Fellowships (2), for original research in biological studies. Established, 1913. Original fund, $43,500. Annually available, $1,000 each.

Upjohn Coöperative Fellowship, for research in organic chemistry. Established, 1919. Annually available, $700.

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REPORT ON PHOTO-ELECTRICITY

Including Ionizing and Radiating Potentials and Related Effects

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PREFACE

The writing of this report on the recent progress in photo-electricity was suggested by the Photo-Electric Committee of the Division of Physical Sciences of the National Research Council. The author wishes to express his appreciation of the valuable suggestions given by the other members of the Committee, viz., Professors R. A. Millikan, K. T. Compton, J. Kunz, and C. E. Mendenhall, to whom the report was sent for comment. Thanks are also due to Professors Compton and Mendenhall for supplying periodicals and summaries of articles, not accessible to the author, and to the authorities of Queen's University for giving ample opportunity for the preparation of the report.

A. Ll. Hughes

Queen's University,
Kingston, Canada,
January, 1921

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ABBREVIATIONS FOR JOURNALS

P. R.	Physical Review.
N. A. S. P.	National Academy of Sciences, Proceedings.
A. P. J.	Astrophysical Journal.
J. O. S. A.	Journal of the Optical Society of America.
J. A. C. S.	Journal of the American Chemical Society.
P. M.	Philosophical Magazine.
P. R. S.	Proceedings of the Royal Society of London.
P. L. P. S.	Proceedings of the London Physical Society.
A. d. P.	Annalen der Physik.
P. Z.	Physikalische Zeitschrift.
V. d. D. P. G.	Verhandlungen der Deutsche Physikalische Gesellschaft.
Z. f. P.	Zeitschrift für Physik.
C. R.	Comptes Rendus.

CHAPTER I

INTRODUCTION

The principal monographs which have hitherto appeared on photo-electricity are the following:

R. Ladenburg: In the *Jahrbuch für Radioaktivität*, 1909.
H. S. Allen: "Photo-Electricity" (Longmans), 1913.
A. Ll. Hughes: "Photo-Electricity" (Cambridge University Press), 1914.
R. Pohl and P. Pringsheim: "Die lichtelektrische Erscheinungen" (Vieweg), 1914.
R. v. Schweidler: "Photo-Elecktrizität" (in Graetz' "Handbuch der Elektrizität und des Magnetismuss" Barth), 1914.
W. Hallwachs: "Die Lichtelektrizität" (published privately).

The present report gives an account of the progress which has been made since 1913. It may, therefore, be regarded as supplementing, and bringing up to date, Allen's "Photo-Electricity" and Hughes's "Photo-Electricity." The division into chapters is that followed in the author's "Photo-Electricity." A chapter has been added on the new and most interesting group of investigations which may, for want of a shorter title, be designated as "Ionizing and Radiating Potentials and Related Effects." This subject, which in many aspects is so closely related to photoelectricity that it is natural to consider it a part of photo-electricity in an enlarged sense, has attracted an immense amount of attention from both theoretical and experimental physicists in recent years. Certain investigations, frequently designated as photo-electrical, because they deal with the change of resistance of materials like selenium under illumination, have not been touched upon. These investigations seem to have little in common with those dealt with in the report; it would be well if some such title as "photo-resistance effects" could be used for them to distinguish them from the effects commonly classed as photo-electric effects.

Perrin has recently published a remarkable paper[1] in which he suggests the important and possible decisive rôle played by radiations in determining chemical reactions, fluorescence and phosphorescence, radioactivity, cosmical evolution and changes of state. According to this theory, the energetics of every change in the configuration of a structure from state A to state A′ may be represented by equations of the type $A + h\nu = A' + h\nu'$, where ν and ν' are the radiation frequencies which change A to A′ and A′ into A, respectively, and $h(\nu - \nu')$ is the heat of reaction. There is considerable direct support for this theory and it leads to a satisfactory explanation of certain facts of velocity of chemical reactions which were not explained on the older kinetic theory. Recent calculations by Langmuir[2] prove that Perrin's theory cannot be applied to many cases of molecular dissociation in the simple form proposed, but suggest some additional source of energy for which the light, or the collision, may act as a releasing "trigger." Yet there is, in the theory, a suggestion that photoelectric action, in an enlarged sense, may be one of the most fundamental and important occurrences in nature.

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[1] *A. d. P.*, **11**, 5–108 (1919).

[2] *J. A. C. S.*, **42**, 2190 (1920).

Throughout the report, it will be often necessary to make use of the quantum relation $Ve = h\nu = hc/\lambda$. It is generally convenient to express V in volts and λ in Ångstrom units, in which case the numerical relation between them is given by:

$$V = \frac{(6.547 \times 10^{-27} \times 2.9986 \times 10^{10})}{4.774 \times 10^{-10}} \times 299.86 \times \frac{10^8}{\lambda}$$

$$V = \frac{12331}{\lambda}$$

CHAPTER II

IONIZATION OF GASES AND VAPORS BY LIGHT

Comparatively little has been done on this subject since 1913, although it was obvious that the subject was very incompletely covered. The technical difficulties are very formidable. In the first place, most gases, if they can be ionized at all, require light of such short wave-length to effect ionization, that very special arrangements have to be made to secure the right kind of light. Fluorite, the most transparent of known substances, begins to absorb strongly just in the region of wave-lengths where ionization of air begins. As it is desirable to have a window between the source of light and the ionization chamber, it becomes very difficult to find a window transparent to the active light. Another obstacle to securing reliable results is that in the region where the ionization of gases begins, the photo-electric effect of metals is enormous, and it becomes a problem how to disentangle the small ionization in the gas from the very large photo-electric effect of the electrodes (even when apparently well shielded) which are generally necessary to separate the ions in a gas.

Ionization of Air. Hughes[1] had obtained results which indicated that air could only be ionized by wave-lengths shorter than about λ 1350. From time to time, various investigators (*e. g.*, Bloch[2]) had obtained results which seemed to show that a weak ionization of air could be obtained by intense light from a mercury lamp (long wave-length limit probably λ 1800). In view of the spurious effects of slight traces of impurities, dust particles, nuclei, etc., so clearly shown in the extensive investigations of Lenard and Ramsauer,[3] it may well be that the slight ionization observed with ultraviolet light from a mercury lamp is not due to a real ionization of the air molecules themselves, but to some obscure subsidiary effect.

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[1] *Proc. Camb. Phil. Soc.*, **15**, 483 (1910).

[2] *C. R.*, **1912**, 903, 1076.

[3] *Ber. d. Heid. Akad.*, 1910–1911.

Ionization of Alkali Vapors. Theoretical considerations indicate that the vapors of the alkali metals should be ionized by light of much longer wave-length than is necessary to ionize air. Against this advantage is to be set the difficulties of working with the alkali metals, the necessity for working at high temperatures to secure an appreciable vapor pressure, and the fact that, if the electrodes become covered with a film of the metal, their photo-electric effect becomes enormous and may well mask any ionization effect.

Gilbreath[1] obtained results which were interpreted as indicating a true ionization of potassium vapor at temperatures not over 65° C. The light used was that from an arc, or from a 500-watt lamp, filtered through glass (shortest wave-length transmitted, probably about λ 3300). Kunz and Williams[2] recently found that caesium vapor was ionized by light of wave-length λ 3190, and that wave-lengths longer than this were quite ineffective. Special care was taken to ensure absence of surface effects.

Discussion. In view of the remarkable utility of the quantum theory in linking up facts in other regions of photo-electricity one naturally looks to it for confirmation of some of the results obtained in ionization of gases by light. Other things being equal, one may perhaps be justified in accepting, tentatively at any rate, those results which link up best with the quantum theory, rather than those which have no obvious connection.

We know that gas molecules, struck by electrons, give out radiation when the energy of the electrons exceeds a certain critical value and become ionized when the energy exceeds another critical value. The potentials associated with these critical values are called radiating potentials and ionizing potentials, respectively. As will be shown in a later chapter, the radiating potential V_R is related to the frequency ν_R of the radiation emitted, as follows:

$$V_R e = h\nu_R = {}^1/_2 m v_R,$$

when h, e, m and ν_R are Planck's constant, the charge on and mass of an electron, and the velocity of the electron acquired from the fall of potential V_R. The ionizing potential V_I is related to a certain convergence frequency ν_I in the spectrum of the gas by a similar equation,

---

[1] *P. R.*, 10, 166 (1917).

[2] To be published shortly.

$$V_I e = h\nu_I = {}^1/_2 m v_I^2.$$

Now, in view of the results in the X-ray region, we should reasonably expect a certain interchangeability in the effects of electron collision and radiation. We may perhaps expect a gas to be ionized whether it is struck by an electron moving with the critical velocity (corresponding to V_I) or illuminated by radiation of the corresponding wave-length, for the same quantum of energy is involved in both cases.[1] Thus, in mercury vapor, we know that direct ionization is produced by electrons of velocity V_I = 10.4 volts, which corresponds to λ 1188, and we should also expect that radiation of this wave-length would be effective also. This is too far in the ultraviolet to allow of easy verification.

No direct ionization of a primary character, of mercury vapor, has been definitely proved for electrons of velocity 4.9 volts, the radiating potential corresponding to the strong line λ 2536 (though effects associated with "low voltage arcs," to be discussed later, show that a strong ionization of a secondary character can be obtained even here). In line with this is the fact that when mercury vapor is illuminated by light of wave-length λ 2536, as in R. W. Wood's[2] experiments, no ionization is observed, although the illuminated gas re-emits the radiation strongly. Similarly, with the alkali metals, we find that no ionization is produced by electrons with velocities above the radiating potential but below the ionizing potential, and we should, therefore, expect that no ionization should be produced by light whose frequency is less than that of the convergence frequency, or limit, of the principal series. This result seems to be borne out by Kunz and Williams' recent experiment. The ionizing potential and radiating potential for caesium are 3.9 volts and 1.5 volts, respectively, which correspond to the limit (λ 3191) and the first line doublet (λ 8946 and λ 8523), of the principal series of doublets in the spectrum of Cs. Kunz and Williams showed that caesium vapor only began to be ionized by light whose wave-length is not far from λ 3191. Should this view be correct, it is difficult to account for Steubing's[1] result that mercury vapor can be ionized by light from a mercury lamp, *i. e.*, by light whose wave-length is longer than λ 1800, and, therefore, far longer than the limit λ 1188 for mercury. It is certainly worth while investigating carefully where ionization of mercury vapor by ultraviolet light sets in, as Steubing's criterion for distinguishing between surface effects and true ionization of the vapor is far from conclusive.

---

[1] It should, however, be pointed out that ultraviolet light of frequency, say λ 2536, incident upon most metals produces a copious flow of electrons. Electrons having the same quantum of energy—4.9 volts—falling on the metal instead of the radiation, do not, as far as we know, produce any analogous effect, so that some caution perhaps is to be observed in carrying ideas from the X-ray region to the ultraviolet light region.

[2] *P. M.*, 23, 689 (1912).

Indirect evidence that there is no ionization by light of wave-length of the frequency corresponding to the radiating potential, is obtained from the fact that when mercury vapor, or any monatomic gas, is subjected to bombardment by electrons of energy just sufficient to call out the radiation, no ionization can be detected, although molecules are being illuminated by radiation from their neighbors. (However, one should bear in mind some recent work of Compton[2] on helium, which indicates that a gas under the influence of its own radiation, when sufficiently intense, is more readily ionized by electron impact than in its normal state.)

Hughes's results on air indicated that air is ionized by light of wave-lengths shorter than λ 1350, corresponding to about 9 volts. Now 9 volts is not far from the values 7.5 volts for nitrogen and 9.5 volts for oxygen, the values formerly associated with the ionizing potentials. Later results have shown that 7.5 volts for nitrogen, however, is a radiating potential rather than the ionizing potential, which is about 18 volts. A similar test has not been made for oxygen, but the analogy of some recent experiments on metallic vapors and on hydrogen and helium would imply that the 9.5 volts for oxygen was the radiating potential and not the ionizing potential.[3] Ionization of air by light of wave-length λ 1350 apparently then contradicts the result tentatively arrived at, that the wave-length which ionizes air corresponds to the ionizing potential and not the radiating potential. It is just possible

[1] *P. Z.*, **10**, 787 (1909).

[2] *P. M.*, **40**, 553 (1920).

[3] Mohler and Foote (*Jour. Opt. Soc. Amer.*, **4**, 49 (1920)) in some recent experiments found that the radiating and ionizing potentials for N_2 are 8.18 and 16.9 volts, for O_2 7.91 and 15.5 volts and for H_2 10.4 and 13.3 volts, thus apparently following the rule observed for monatomic gases that the lower critical potential is always a radiating potential. However, Franck, Knipping and Kruger, and Compton find that the lower critical potential for H_2 is definitely an ionizing potential. In view of this, one may perhaps require further proof that the lower critical potential for diatomic gases is always a radiating potential as appears to be the case for monatomic gases.

that when a molecule is already in an abnormal state due to the absorption of radiant energy of wave-length correponding to the radiating potential, further radiant energy of the same wave-length may cause it to be ionized. (This speculation, and it must be recognized merely as such, implies, in other words, that intense radiation may produce ionization when feeble radiation would not.) The recent work of Compton, just referred to, is suggestive in this connection.

It is recognized, of course, that the effect of radiation impinging on an atom is not exactly analogous to the effect of a collision with an electron, for the absorption of radiation is probably a continuous process, while the absorption of energy through an electron collision is essentially discontinuous. Again, from the experiments of McLennan and others, there is only *strong* absorption at the isolated wave-lengths of the principal series, whereas electrons moving with *any* velocity between the radiating potential and the ionizing potential give rise to radiation.

The whole subject is full of obscurities and suffers from lack of experimental data. A systematic investigation, with improved methods, of the ionization of gases and vapors by light, should repay investigation. It is of considerable interest to ascertain definitely whether the wave-length of the light which ionizes a gas is related to the ionizing potential by the quantum relation.

CHAPTER III

THE ENERGY OF PHOTO-ELECTRONS

Exact measurements of the velocities of photo-electrons are of the utmost importance in furnishing evidence for testing the theories of the photo-electric effect. The photo-electric effect was among the first effects to which the quantum theory was applied. In 1905, Einstein proposed a law governing the relation between the maximum emission energy of the photo-electron and the frequency of the light causing its emission. Each advance in experimental accuracy has given a more accurate verification of its correctness. According to Einstein, the energy of a photo-electron ejected from a substance by light of frequency ν is equal to the energy associated with a quantum of light of that frequency, viz., $h\nu$, less the loss of energy in getting out of the substance. The relation may be written

$$Ve = h\nu - V_0e$$

where Ve is the energy of the electron after leaving the surface (V being the voltage necessary to stop it), and V_0e is the energy lost in getting out of the substance.

Some implications of this equation are as follows:

(1) The energy of a photo-electron is a linear functon of the frequency of the light.

(2) The slope of the line connecting the energy and the frequency is the well-known quantum constant "h."

(3) The long wave-length limit of the photo-electric effect, or the "photo-electric threshold" (to introduce a convenient term), is that for which the electron escapes with zero energy. Hence, the frequency ν_0 of the photo-electric threshold is given by

$$0 = h\nu_0 - V_0e$$

so that, once we know the threshold for any substance, we know the work necessary to pull a photo-electron out of the substance.

Up to the date at which this report begins, these implications had been confirmed through the work of Richardson and Compton and of Hughes. In view of the importance of testing the implications to as high a degree of accuracy as possible, further work was necessary as the researches referred to yielded a value of "h" from 10 per cent to 20 per cent smaller than the accepted value, and the limited range of wave-lengths naturally restricted the precision with which the other relations could be tested. (When these results were obtained, there was a certain amount of speculation as to whether one could expect complete agreement between the

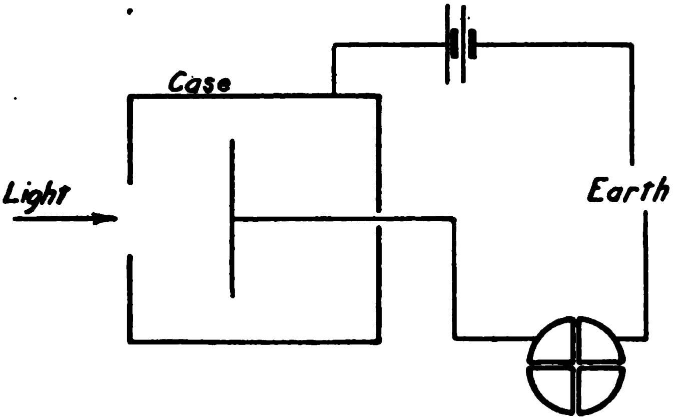

FIG. 1.

photo-electric value and the theoretical value of "*h*," as it was conceivable that the slope of the line connecting energy of photo-electrons and frequency might in some way be slightly affected by the nature of the substance or by other conditions.)

METHOD OF MEASUREMENT OF VELOCITIES

The most common way of measuring the velocities of photo-electrons is to measure the photo-electric current with various retarding fields. Consider a small illuminated surface surrounded by a considerably larger conductor, which we may call the "case," as in fig. 1. The photo-electric currents from the illuminated electrode to the "case," as functions of the applied accelerating or retarding potential, take the form shown in fig. 2*a* (where the saturation currents are adjusted to the same value for each wave-length). In general, the curves imply that while some electrons require a retarding field to stop them, the part of the curves between the ordinates at O and A apparently indicates that some photo-

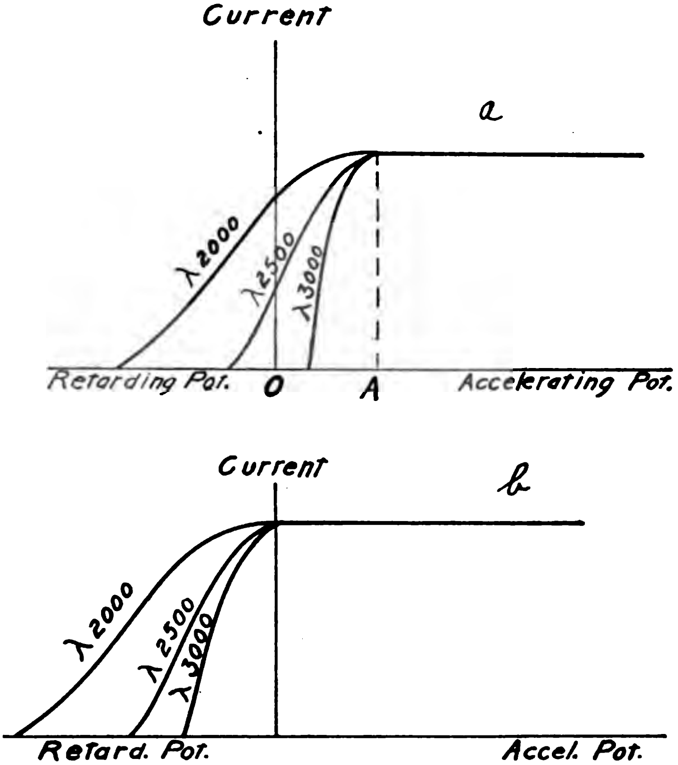

FIG. 2.

electrons actually need a small accelerating potential to pull them out. Richardson and Compton were the first to interpret this correctly. The actual potential difference between the illuminated electrode and the case in fig. 1 is not the applied potential alone, but this, plus or minus the *contact difference of potential* between the case and the electrode. When this is correctly allowed for, the curves are all shifted with the result that the point P falls accurately on the zero ordinate, fig. 2*b*. It is now seen that the photo-electrons have emission velocities between zero and a maximum, characteristic of the light, and that saturation is obtained as soon as the retarding potential is diminished to zero, provided effects due to electrons reflected from the case are guarded against. (The displacement of the saturation point from the zero ordinate may often be a convenient, though an inaccurate, way of measuring contact potential difference as Richardson and Compton pointed out.) On plotting the maximum emission energies (corrected for contact potential differences) against the corresponding frequencies, a straight line as shown in fig. 3 is obtained. The slope of this line should, according to Einstein's equation, give "*h*," and its intercept with the abscissa, the photo-electric threshold.

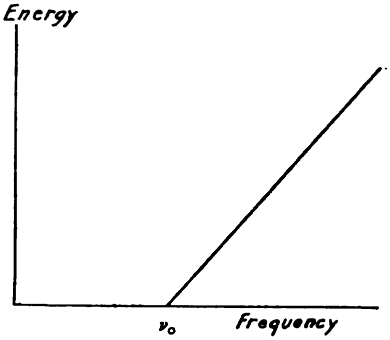

FIG. 3.

EXPERIMENTAL RESULTS

Kadesch[1] made an advance in that he used Na or K as the illuminated material and oxidized copper as the material for what we have termed the case, fig. 1. These two metals, being photo-electrically active in the visible spectrum, enable one to use a wide range of wave-lengths for investigation. It is difficult to ensure that no light falls on the inside of the "case" (either by reflection or otherwise). The photo-electric effect produced by this light causes a small current to flow in the opposite direction to the one under investigation, viz., that from the illuminated electrode, when the potential is such as to retard the main stream of photo-electrons. This "return" current reduces the direct current everywhere, and its effect becomes the more marked the smaller the direct current. Hence it is that just about the point at which the direct current vanishes altogether, *i. e.*, the point giving the maximum emission energy, an incorrect value is obtained. This error can be avoided by limiting the investigation to a range of wave-lengths over which the illuminated substance is photo-electrically sensitive, and over which the "case" is insensitive. This was realized in Kadesch's experiments, as the photo-electric threshold of copper oxide is far in the ultraviolet, while the sodium and potassium are sensitive in the visible spectrum. Kadesch found the linear relation to hold and that the experiments on K and Na gave, respectively, the values of 6.16×10^{-27} and 6.09×10^{-27} for "h."

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[1] *P. R.*, **3**, 367 (1914).

Millikan[1] examined the question with great thoroughness and took every precaution to avoid spurious effects. He used as his sensitive metals, Li, K and Na. These metals were so mounted that fresh surfaces could be cut and exposed in vacuo. The contact difference of potential with respect to the "case" was measured in the same vacuum with the photo-electric measurements and almost simultaneously with them, so that there could be no error from time changes. The case was made of oxidized copper whose threshold was slightly above λ 2536 in one set of experiments and slightly below it in another set. Hence, a range of wave-lengths from λ 2536 to about λ 5461 was available in the case of Na and to about λ 4339 in the case of Li, free from the possibility of a spurious effect, of the kind referred to in discussing Kadesch's experiments.

Another source of spurious effects is that the monochromator when set to isolate any particular wave-length in the spectrum (of a mercury arc, for example) does not isolate it completely. On account of internal reflections in the monochromator of one kind or another, small amounts of scattered light of all wave lengths pass out along with that portion of the spectrum which the monochromator is set to isolate. The stray light of shorter wave-length than that with which the investigator is working is troublesome in that it causes the emission of electrons of energies greater than those corresponding to the wave-length for which the monochromator is set. The stray scattered light of shorter wave-length than that in use was frequently stopped out in Millikan's experiments by means of light filters whose transparency ended just beyond the short wave-length side of that part of the spectrum which the monochromator was set to isolate. Large photo-electric currents were obtained by using an intense source of light and by using surfaces freshly prepared in vacuo. This enabled the points corresponding to the maximum emission energies to be determined with much precision. It was concluded that the value of "h" was 6.569×10^{-27} from experiments on sodium and 6.584×10^{-27} for experiments on lithium. The final value for "h" is given as 6.56×10^{-27} to $^1/_2$ per cent. Millikan also verified with great accuracy the result that the photo-electric thresholds of the metals were given by the intercept of the line, representing the linear relation between the emission energies and the frequency, and the potential axes (Fig. 3), due allowance being made for contact potential difference.

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[1] *P. R.*, 7, 355 (1916).

Sabine[1] attached a photo-electric cell, in which Zn, Cd and Cu were the active metals, to a vacuum spectroscope which enabled him to use exceptionally short wave-lengths, the shortest being λ 1250. By combining his results for λ 1250 with those of other experimenters for longer wave-lengths, he arrived at values of "h" fairly close to the accepted values ($6.58, 6.71, 7.23 \times 10^{-27}$). It was admitted that the procedure of combining results in this way was less satisfactory than if observations on all wave-lengths had been taken under identical conditions.

Ramsauer[2] investigated the emission energies of photo-electrons by means of a method different from the retarding electric field method usually adopted. The photo-electrons were deflected by a magnetic field and those within a narrow range of velocities were sorted out by suitably placed slits. Thus the distribution of velocities could be determined. A great drawback of this method is that the number of photo-electrons available after being sorted out is very small in comparison with the number handled in the usual electric field method. Ramsauer concluded that there is no such thing as a definite maximum emission velocity for photo-electrons, and also that the distribution of energies of the photo-electrons is the same before and after passing through the surface. He obtained a linear relation between the most probable velocity and the frequency of the light. With regard to his contention that no definite maximum emission velocity exists, Millikan[1] points out that the experimental arrangements were unsatisfactory, chiefly because the part of the spectrum supposed to be isolated by the monochromator was contaminated by considerable amounts of light of shorter wave-length. A detailed criticism will be found in Millikan's paper.

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[1] *P. R.*, **9**, 210 (1917).

[2] *A. d. P.*, **45**, 1120 (1914).

THE PHOTO-ELECTRIC THRESHOLD

Important consequences follow from a consideration and amplification of Einstein's equation. Millikan has examined it in detail, and the following account is based on his papers.[2]

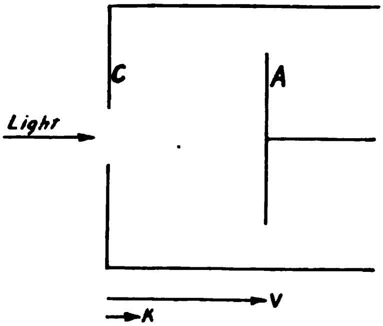

FIG. 4.

Consider a metallic surface, A, emitting electrons when illuminated by light of frequency ν. The energy of the fastest of these electrons is obtained by measuring the retarding potential, V volts, necessary to prevent them reaching C. The field acting on the electrons includes the contact difference of potential between C and A, say K volts. Hence

$$(V + K)e = h\nu - p \qquad (1)$$

where p is the energy lost in passing from the system where the photo-electron starts, to a point just outside the surface. (A is *electro-positive* to C, if K assists V.) Experiments (see previous section) have shown that the smallest frequency ν_0, for which the surface A has a photo-electric effect, is that one for which the electron emerges with negligible velocity (*i. e.*, $V + K = 0$), and it then follows, since $0 = h\nu_0 - p$, that

$$(V + K)e = h\nu - h\nu_0. \qquad (2)$$

If now a surface, B, be substituted for A and illuminated by the same light, we have a similar equation

$$(V' + K')e = h\nu - h\nu_0' \qquad (3)$$

where V', K', and ν_0' refer to the stopping potential, the contact potential with respect to the case, and the photo-electric threshold of the surface B. Subtracting (2) from (3) we get

$$(K' - K) = \frac{h}{e}(\nu_0 - \nu_0') - (V' - V) \qquad (4)$$

i. e.,

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[1] *P. R.*, **7**, 18 (1916).

[2] *Ibid.*, **7**, 18, 355 (1916).

$$\left\{\begin{matrix}\text{contact potential}\\ \text{between A and B}\end{matrix}\right\} = \frac{h}{e}\left\{\begin{matrix}\text{frequency difference}\\ \text{of thresholds}\end{matrix}\right\} - \left\{\begin{matrix}\text{difference between}\\ \text{stopping potentials}\end{matrix}\right\}.$$

This equation is one which can be checked up by experiment. Before doing so, it is well to look at it from another angle. Let us regard p in equation (1) as being made up of two parts, p_1, the energy lost when the electron leaves its parent system and becomes a "free" electron, and p_2, the energy lost by the free electron in passing through the surface. p_2 may be conveniently written as $V_s e$, where V_s is the intrinsic potential of the metal. ($V_s e$ is probably identical with the energy lost by an electron in passing through the surface in the thermionic effect.) Equations (2) and (3) now become

$$(V + K)e = h\nu - V_s e - p_1$$

$$(V' + K')e = h\nu - V_s' e - p_1'$$

which on subtracting yield

$$(V' - V) + (K' - K) = (V_s - V_s') - \frac{p_1' - p_1}{e}.$$

As the difference between the intrinsic potentials $(V_s - V_s')$ is nothing other than the contact difference of potential $(K' - K)$, we get

$$(V' - V) = \frac{p_1 - p_1'}{e}. \qquad (5)$$

If this view of the mechanism of the photo-electric effect be correct, then a careful comparison of equation (4) with the experimental data will tell us whether $(V' - V)$ for two metals is finite or zero, and then by (5) whether any difference exists in the p_1's, *i. e.*, in the work necessary to extract the photo-electron from the parent system and make it a "free" electron.

The experimental evidence obtained by all observers is now in agreement that when any two different metals are brought into rapid succession before a Faraday cylinder into which they discharge photo-electrons, the stopping potential for a given value of the wave-length incident upon them is exactly the same. Hence, the difference $(V - V')$ in each case is shown by experiment to be zero, and equation (4) degenerates into the following equation:*

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* The stopping potential for a given wave-length is, however, often observed to change with time as in Millikan's experiments, so that if much time elapses between measurements of the stopping potentials for two different metals, the experimental equation will have the form of (4) and the observed values of $(V' - V)$ will measure a contact E. M. F. which is due to a transient surface charge rather than to an intrinsic property

$$K' - K = \frac{h}{e}(\nu_0 - \nu_0'). \tag{6}$$

As Millikan points out[1] the interpretation of equation (6) can only be that the energy after *escape* of the electron from the atom is always equal to $h\nu$, the absorbed energy being, contrary to the physical theory which guided Einstein, greater than $h\nu$, or else that the same energy is required to detach an electron from all atoms (an impossible conclusion) or else that the photo-electrons are from the beginning the free electrons rather than the electronic constituents of the atoms. The first of these conclusions is exactly the one to which Barkla was led by his work on X-rays. On the other hand, the last conclusion is very difficult to reconcile with the photo-electric properties of insulators, which have no free electrons, and also with the independence of photo-electric currents of the temperature.

Whichever of the foregoing interpretations be made as to equation (6), it requires that the whole of the energy $h\nu_0$ of the electron be expended in passing *through the surface* and hence that $h\nu_0$ is a measure of V_s, the intrinsic potential of the metal. Now, V_s is given by thermionic experiments, and V_0 may be obtained from the photo-electric thresholds ($V_0 e = h\nu_0$). The following is a table drawn up for comparison. Unfortunately, the variations in the values for the thermionic results are only equalled by the uncertainty in the photo-electric quantities. For example, the values for V_s for Pt (taken from O. W. Richardson's "The Emission of Electricity from Hot Bodies") range from 4.1 to 6.6

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of the metal. This, as Millikan points out, enables the distinction to be drawn between intrinsic, or true, contact E. M. F.'s and spurious contact E. M. F.'s due to surface charges. In Millikan's experiments reported in 1916 such charges developed on the copper oxide surface, due presumably to the entanglement of free electrons in this surface. This accounts for the difference which was found between the measured contact E. M. F. between Na and CuO, *i. e.*, $(K' - K)$, and $\frac{h}{e}(\nu_0 - \nu_0')$ as measured for the same substances. In later experiments, soon to be published, Na and Li were brought in rapid succession before the Faraday cylinder covered with CuO and it was found that the stopping potentials were identical for the two metals. The static charge on the CuO was the same in both measurements and therefore was eliminated. If, however, a considerable time elapsed between the times of testing the Na and the Li so that the static charge on the CuO had opportunity to change, the stopping potentials were found to be different. To summarize briefly, Millikan finds that equation (4) is always correct, whether static charges are present in the CuO, or not, but when they are eliminated equation (6) is found to hold.

[1] *P. R.*, **7**, 26 (1916).

volts. 5 volts is taken here as being possibly the most reliable value. The table is merely given to illustrate the order of the correspondence. The evidence is quite insufficient to warrant its use in deciding for, or against, a connection between the two effects. Further investigation is required, but the experimental difficulties are very considerable. At best, one can say that there is only the same order of values for Pt and W, while for CuO there is a considerable difference. Possibly the value of p_1, the part of the energy lost in detaching the photo-electron from its parent system, and making it into a free electron, is much greater for a non-metal, than the energy lost in passing through the surface, hence the big discrepancy for CuO.

Metal	Photo-electric threshold			Thermionic V_s	
	λ_0		V_0		
Pt	2800	(Richardson and Compton)	4.4 volts	5.0 volts	(Richardson *loc. cit.*)
W	2300	(Hagenow[1])	5.7 volts	4.3 volts	"
CuO	2500	(Millikan)	5.0 volts	1.9 volts	"

FLUCTUATIONS IN THE PHOTO-ELECTRIC THRESHOLD. DEPENDENCE ON THE CONTACT DIFFERENCE OF POTENTIAL.

At the beginning of the period covered by this report, it was recognized that the photo-electric threshold obtained experimentally was largely determined by insignificant surface conditions, presumably arising from re-acting gas, but there did not seem to be any weighty reasons why it should not be possible to arrive at the real value of a photo-electric threshold characteristic of the metal under investigation, uninfluenced by fugitive surface conditions. The photo-electric thresholds, and through them the potentials given by the quantum relation for a large number of metals might well yield an interesting and valuable series of atomic constants. However, from this point of view, the experimental results have been disappointing, for they have shown clearly how, time after time, almost imperceptible changes in conditions can affect the value of the threshold and consequently make it almost impossible to decide which, if any, of the many experimental values

[1] *P. R.*, 13, 415 (1919).

obtained is the real value of the photo-electric threshold characteristic of the substance under examination.

But few experiments have been carried out on the shift of the photo-electric threshold. A much larger number of investigations have been carried out on the effect of varying the conditions on the total photo-electric current. There is no doubt but that conditions which change the total photo-electric effect of a substance (*i. e.*, its photo-electric sensitivity to unresolved light) are almost always due, in part, to a shift in the photo-electric threshold. Thus conditions which shift the photo-electric threshold towards the red end of the spectrum naturally increase the total photo-electric effect, as in this way a greater portion of the spectrum becomes available photo-electrically. Unfortunately, in many cases, not sufficient information is given to enable one to infer what happens to the threshold when conditions are altered so as to change the total photo-electric effect. The photo-electric threshold being a more definite constant than the total photo-electric effect, insofar as its use for theoretical discussions goes, it is highly desirable that observations be made on it in all experiments on variations in the total photo-electric effect whenever possible. In the following discussion, only those investigations from which inferences as to the shift of the photo-electric threshold can be made, are considered.

Pohl and Pringsheim[1] found that the photo-electric threshold for new metallic surfaces (generally obtained by distillation of the metal in vacuo) moved spontaneously in the course of a few hours over a range of an octave of frequencies or more. Thus the photo-electric threshold for a calcium amalgam moved from λ 3500 to λ 6000 and the photo-electric threshold for newly distilled Mg moved from λ 3500 to λ 5500 in twenty-four hours, without any apparent cause.

In 1913 and 1914, it was urged by a number of physicists—Fredenhagen among others—that both the thermionic and photo-electric effects were essentially effects associated with the chemical action between the metal and an invisible film of reacting gas, and that both effects would disappear for metals completely denuded of gases. In support of this, Kustner[2] found that for newly produced surfaces of zinc in a vacuum from which all re-acting

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[1] *P. Z.*, **14**, 111 (1913).

[2] *Ibid.*, **15**, 68 (1914); *A. d. P.*, **46**, 893 (1915).

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gases were most carefully excluded, there was no photo-electric effect. As he used a quartz mercury lamp, we may consider that his shortest wave-length was λ 1849. A less radical departure would be to conclude that the photo-electric threshold for zinc had been merely displaced to a value below λ 1849. (The chemical action theory, so far as thermionics is concerned, was disproved by O. W. Richardson.[1]) This view received support from some experiments by Hughes[2] on the contact difference of potential between platinum and newly distilled zinc. Ordinary clean zinc is electropositive to platinum by about a volt. Newly distilled zinc was frequently found to be slightly *electronegative* to platinum. However the slightest trace of a re-acting gas served to make it strongly electropositive. The electropositive character as a function of the amount of gas admitted to the zinc may be represented diagrammatically as in fig. 5. The relations between the photo-electric threshold and the contact difference of potential brought out in the preceding section would then indicate that the threshold for newly distilled zinc should occur at a shorter wave-length than that for ordinary platinum (λ 2800), but that a trace of gas would shift it well towards the visible spectrum. This is precisely what happened in Kustner's photo-electric experiments. It is probable that the experimental conditions in Kustner's work allowed a more thorough removal of re-acting gases than in these experiments on the contact potential, and this would explain why the threshold in Kustner's experiments had been displaced further than might be anticipated from these experiments. Kustner's experiments imply that the intrinsic potential for perfectly gas-free zinc is above 6.7 volts, calculated from λ 1849 (and assuming that p_2 in Millikan's form of Einstein's equation is zero, or does not enter into $h\nu_0$), a value which, it should be remarked, is appreciably greater than the thermionic value for platinum and tungsten obtained under conditions considered gas free. The whole ques-

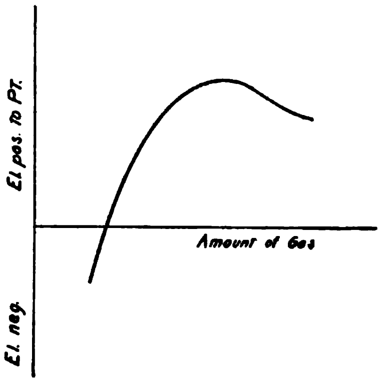

FIG. 5.

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[1] *P. M.*, 26, 345 (1913).

[2] *Ibid.*, 28, 337 (1914).

tion of contact differences of potential between gas-free metals may well repay investigation.

Experiments on the photo-electric threshold of the alkali metals have yielded conflicting results. Wiedmann and Hallwachs[1] found that the photo-electric activity of K disappeared after repeated distillation in the highest vacuum. The shortest wave-length available in their light was probably λ 3300. Pohl and Pringsheim,[2] on the other hand, found that the photo-electric effect of K was not appreciably affected by prolonged boiling, and, in particular, that the selective effect remained unchanged. The shortest wave-length available was about λ 4360. Wiedmann[3] investigated the matter again and found that the photo-electric effect of K was reduced to less than 1 per cent after repeated distillations, and, moreover, that the selective effect disappeared altogether. Werner[4] found that with sputtered platinum, the photo-electric current increased considerably with the age of the surface, especially for the longer wave-lengths. The photo-electric threshold also underwent a slight displacement towards longer wave-lengths. Elster and Geitel[5] found that boiling and re-distilling potassium for as long as 214 hours had no effect on either the normal or the selective effects. A similar result was found for cadmium, the photo-electric current being substantially the same whether the cadmium had been distilled seven times or only once. By investigating the effect with monochromatic light of different frequencies, Millikan and Souder[6] found that the behavior of Na immediately after exposing a fresh surface in a very good vacuum depended very largely on the frequency of the light used. Fig. 6 shows the sensitivity to various frequencies at successive time intervals after renewing the surface. Under conditions when the absence of gases was considered most complete, the Na was found to be quite insensitive to λ 5461 immediately after exposing a new surface by cutting, but after about two minutes it began to be sensitive and increased to a maximum in about twenty minutes. Its behavior with regard to λ 2536 under similar conditions was quite different, the sensitivity at the beginning being very high but falling as the surface grew older. It was

[1] *V. d. D. P. G.*, **16**, 107 (1914).
[2] *Ibid.*, **16**, 336 (1914).
[3] *Ibid.*, **16**, 343 (1915).
[4] *Ark. för. Mat Astr. och. Fysik.*, **8**, 1 (1913).
[5] *P. Z.*, **21**, 361 (1920).
[6] *P. R.*, **4**, 73 (1914); *N. A. S. P.*, **2**, 19 (1916).

considered that the λ 2536 effect was that of the metal itself, while the rise and fall of the λ 5467 effect corresponded to the production, and subsequent decay, of a new substance formed at the surface by the reacting gas. The substance has the property of making the surface more electropositive. Millikan[1] mentions that the contact difference of potential between Na and a CuO surface was decreased by exposing a new Na surface, after which it gradually rose, a result analogous to that of Hughes obtained with freshly distilled zinc.

Much more remains to be done in establishing the exact nature of the causes giving rise to the shifts of the photo-electric threshold. The problem seems to be intimately connected with that of the nature of the contact potential. Questions have been raised from time to time as to whether a contact difference of potential exists between really pure, gas-free, metallic surfaces, *i. e.*, whether it is an inherent property of the metal or an incidental property of the surface. Further information as to this can hardly fail to have an important bearing on the nature of photo-electric thresholds.

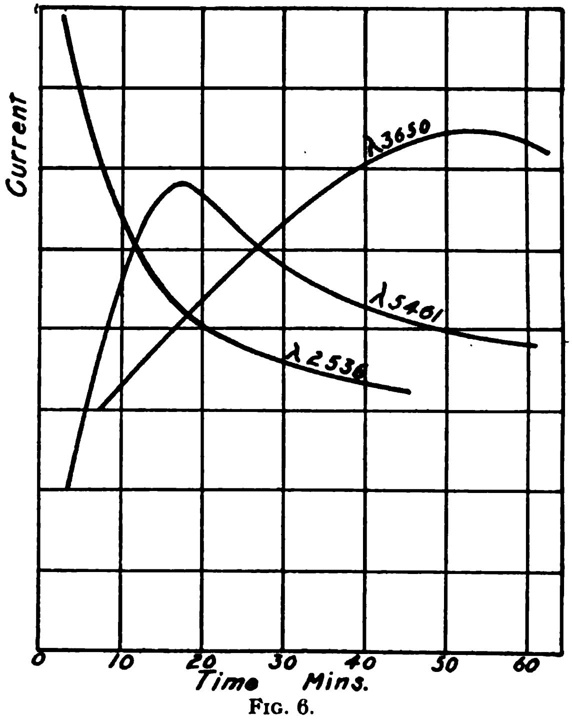

FIG. 6.

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[1] *P. R.*, 7, 355 (1916).

CHAPTER IV

TOTAL PHOTO-ELECTRIC EFFECT

PHOTO-ELECTRIC CURRENT AND LIGHT INTENSITY

An important question which has been the subject of many investigations since 1913, as well as before it, is that of the relation of the magnitude of the photo-electric current from an illuminated surface to the intensity of the incident light. Generally speaking, the results have pointed to the conclusion, which one would expect on theoretical grounds, that the photo-electric current is proportional to the intensity of the light. Yet some careful investigations indicated a departure from the proportionality law. In view of important practical applications of the law to the measurement of light intensity, many researches have been carried out to test its validity.

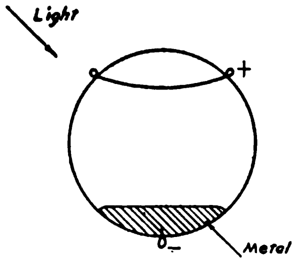

FIG. 6*a*.

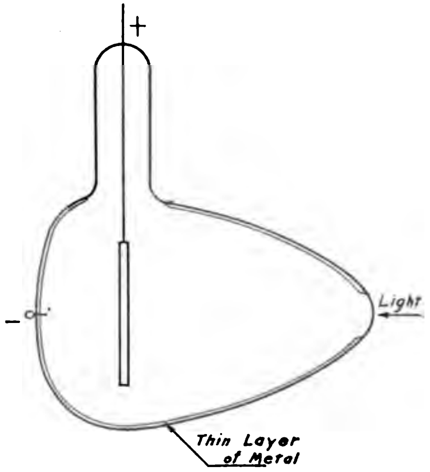

FIG. 6*b*.

Investigations have been made chiefly on the alkali metals inasmuch as these are sensitive to visible light. The photo-electric cell consists essentially of a surface to be illuminated, forming one electrode, and another electrode, whereby an accelerating potential can be applied to drive the photo-electrons across the cell. Two extreme types are shown in the diagrams (figs. 6*a*, 6*b*). The pure photo-electric effect is that obtained in the absence of any gas. However, to use the magnification (which may conveniently amount to a 100-fold or more) of the photo-electric current by ionization by collision, it is customary to fill the cell with gas at a pressure of about 1 mm. To avoid reactions between the sensitive surface and the gas, the gas is usually He, A, or Ne. By passing a glow discharge through the cell when it contains hydrogen, a hydride of the alkali metal is formed which is much more sensitive even than the pure metal. In such cells it is the practice to replace the hydrogen after the new sensitive surface has been formed by an inert gas.

Now, in testing the proportionality law, the fundamental thing to be investigated is the ratio of the number of photo-electrons liberated at the surface to the intensity of the light. In the absence of any gas, it is evident that saturation must be obtained, while, in the presence of a gas, the multiplying factor due to ionization by collision must not vary.

An extensive series of experiments was made by Ives[1] and also by him in conjunction with Dushman and Karrer.[2] In the earlier of these papers, results were given indicating that the ratio of the current to the intensity of the light was not constant, but was a complicated function of the intensity, applied potential, illuminated surface, and gas. The cells usually contained potassium treated by a glow discharge in hydrogen, and filled with an inert gas at a low pressure to magnify the effect. Finally, the source of the departure from the linear relation was traced down to the presence of insulating surfaces in the cells as usually constructed. These surfaces generally acquire charges from photo-electrons, or ions, hitting them, and these charged surfaces, in turn, distort the electric field which affects the flow of electricity across the cell. In view of the fact that these insulating surfaces (which may not be perfect insulators) may acquire different surface charges under different conditions of illumination, field intensity, etc., it is little wonder that the effect could be otherwise than an incalculable modification of the strict proportionality. The final result of this series of investigations is that a strictly linear relation can be obtained between illumination and photo-electric current, provided close attention is paid to the design of the cell. They point out that the design of the cell due to Hughes,[3] in which the inside of a bulb is almost completely covered with distilled sodium and the other electrode is a brass rod (as shown in fig. 6*b* above). so that there are no exposed insulating surfaces anywhere near where the current flows, satisfies the necessary conditions. Ives found it impossible to make cells identical in properties. The curve of sensitivity with wave-lengths varied considerably from one cell to another prepared under identical conditions. Kunz[1] found that when the potential, pressure and light intensity were so adjusted that a visible glow was to be seen in the photo-electric cell, the current was not proportional to the light intensity. Evidently, the magnification due to ionization by collision is no longer a constant under these conditions.

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[1] *A. P. J.*, **39**, 428 (1914); **40**, 182 (1914); **46**, 241 (1917).

[2] *Ibid.*, **43**, 9 (1916).

[3] *P. M.*, **35**, 679 (1913).

Elster and Geitel[2] discussed the various ways whereby faulty design of a photo-electric cell causes an apparent departure from the proportionality law. When the possibility of charges on the glass wall was avoided, they found strict proportionality from 30,000 lux ($^1/_3$ of sunlight) down to 6×10^{-4} lux. (A *lux* = 1 candle metre.) The lowest illumination with a potential of 200 volts across the cell was 2.4×10^{-6} lux and gave a current of 1.8×10^{-12} amp. In a second paper[3] they found an apparent departure from the proportionality law with strong light, but this was traced down to a discontinuity in the magnification of the photo-electric current by ionization by collision. In this region, they state that if the cell is used completely evacuated, the strict proportionality is observed. In a later paper[4] they found that the proportionality law held down to light as feeble as 3×10^{-9} erg per sq. cm. per sec. for blue light and 2×10^{-7} erg. per sq. cm. per sec. for orange light, the former value being below the "threshold" value for the human eye.

Kunz and Stebbins[5] found that the proportionality law held exactly for a rubidium cell containing neon. Kunz[6] found a slight departure from the proportionality law with high intensities. With the older type of spherical cell with illuminated central electrode, there was a marked departure from the proportionality law, while a cell in which the two electrodes were parallel plates gave the best agreement with the law. Proportionality was found to hold over a range from 1 to 1300.

A consideration of these results, taken altogether, seems to point beyond all doubt to the result that there is a strict proportionality between intensity of illumination and the number of photo-electrons emitted, and that this holds over a wide range extending from illumination too feeble to be visible, to illumination comparable with sunlight. Departures from the law appear to be due to faulty design in the cell which permits spurious effects, or else to the alteration in the multiplying factor of ionization by collision under extreme conditions.

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[1] *P. R.*, **13**, 310 (1919).
[2] *P. Z.*, **14**, 741 (1913).
[3] *Ibid.*, **15**, 610 (1914).
[4] *P. Z.*, **17**, 268 (1916).
[5] *P. R.*, **7**, 62 (1916).
[6] *A. P. J.*, **45**, 69 (1917); *P. R.*, **9**, 175 (1917).

PHOTO-ELECTRIC PHOTOMETRY

The numerous articles on the applications of the photo-electric cell to the measurement of light intensities show how valuable such cells have been found for this purpose. They are of particular value under conditions where thermopiles are unsatisfactory and difficult to work with, as, for example, with weak visible light or in the ultraviolet. For satisfactory work as measurers of light intensity, it is, of course, necessary to ensure that the design of the cell is such that there is no departure from strict proportionality between the light intensity and current. For applications of the kind contemplated here, it is well to arrange for as high a degree of sensitivity as one can get. First, arrange to use as much of the incident light as possible. When light falls upon a clean sodium surface, probably over 99 per cent is reflected and so, in a cell of the first type in fig. 6*a*, is lost so far as the photo-electric effect is concerned. By means of a design of cell suggested by "black body enclosures" as used in the study of heat radiation, such as the cell described by Hughes[1] (fig. 6*b*) it is possible to trap almost all the light and so make it effective photo-electrically. Such a cell is prepared by distilling an alkali metal on to the inside of a suitably shaped bulb, and arranging to leave a small aperture just big enough for the light to enter. Light which enters is reflected to and fro inside and each time contributes to the photo-electric effect. To increase the sensitivity further, it is customary to pass a glow discharge through hydrogen in the cell to convert the metal into the more sensitive hydride. Finally, one makes use of the magnification of the original photo-electric current from the surface, by filling the cell with an inert gas, such as argon, and choosing the most favorable accelerating potential to give the most convenient magnification.

One disadvantage of photo-electric cells is that no two cells have exactly the same sensitivity for different wave-lengths. So, when one uses photo-electric cells to compare energies in different parts of the spectrum, it is necessary to standardize each cell, either by a thermopile (using intense enough light, of course, to affect it) or by using a source of light in which the distribution of energy is known. For studying variations in monochromatic light, no such calibration is necessary.

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[1] *P. M.*, 35, 679 (1913)

As we have seen, a cell of the type designed by Elster and Geitel is more sensitive than the human eye. Such a cell so arranged that its effect is strongly magnified by the use of three electrode valves, should open up possibilities of a big field of quantitative measurements in regions hitherto unexplored (*e. g.*, weak phosphorescence, scattering of light, resonance emission, etc.).

A method of magnifying the effect of a photo-electric cell by a three electrode valve has been described by Kunz,[1] and by Pike.[2] Pike obtained amplifications as large as 15,000. Meyer, Rosenberg and Tank[3] obtained amplifications up to about 15,000. In later experiments values up to 125,000 were obtained. They found that the amplification was quite constant for small photo-electric currents.

The photo-electric cell is well adapted for measuring stellar magnitudes, fluctuations of star light, and corona intensities during eclipses. It will be remembered that unless spectral resolution be resorted to, the sensitivities of photo-electric cells differ from each other and from that of the human eye. Just as the eye is most sensitive to yellow-green light, so cells containing Cs, Rb, K, Na, Cd and Zn have their own proper maxima running from yellow far into the ultraviolet, in the order indicated. Miss Seiler[4] found that the maxima for photo-electric cells were at λ 4050, λ 4200, λ 4410, λ 4730, and λ 5390 when the surfaces were Li, Na, K, Rb, and Cs. In every case, sensitizing the surface by passing a glow discharge through hydrogen over the alkali metal caused a shift in the maximum towards the longer wave-lengths.

Elster and Geitel[5] describe photometers with Cd or Zn as the sensitive surface, specially suitable for measurements on the ultra-violet radiation of the sun and stars. Guthnick[6] used a photo-electric cell to determine the amount of light reflected by the planets from the sun at different parts of their orbit. A. F. and F. A. Lindemann[1] discuss the various applications of photo-electric cells to astronomy. Among other applications may be mentioned the study of the light reflected by the planets for evidence as to fluctuations in the light of the sun. They also point out the usefulness of photo-electric cells in the study of the light from diffused luminous areas such as nebulae and comets.

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[1] *P. R.*, 10, 205 (1917).

[2] *Ibid.*, 13, 102 (1919).

[3] *Archeves des Sciences*, 2, 260 (1920).

[4] *P. R.*, 15, 550 (1920).

[5] *P. Z.*, 15, 1 (1914); 16, 405 (1915).

[6] *Nature*, 103, 53 (1919); *Astr., Nachr.*, No. 4976.

Kunz and Stebbins[2] gave details of the use of photo-electric cells for studying the light from the corona during the eclipse of June 8, 1918. Stebbins and Dershem[3] used potassium cells for studying the fluctuations of the light from Nova Aquilae, No. 3. Hulburt[4] used a photo-electric cell successfully for investigating the reflecting power of metals in the ultraviolet region. Nathanson[5] investigated the reflecting power of the alkali metals by a photo-electric method.

A recent paper by Elster and Geitel[6] deals with an apparent continuation of the photo-electric effect for potassium for a short time after the light is cut off. This was found to be due to a weak phosphorescence in the photo-electric cell. This effect may introduce an error in photo-electric photometry when light intensities are changing rapidly.

It is convenient here to give a short account of the discovery of a new and exceedingly interesting kind of photo-electric effect, which was discovered by Mr. Shenstone in the Physics Laboratory of Princeton University. The photo-electric current from a bismuth plate was found to depend very much on the magnitude of a current passing *through* the plate. A thin square plate of bismuth was mounted in a vacuum so that an electric current could be passed across it, *i. e.*, from one side of the square to the opposite side. The photo-electric current from the bismuth, illuminated by light from a mercury arc, was found to be independent of the current through the bismuth, as long as it was below 1.1 amperes. Any increase beyond this up to 3 amperes

[1] *Roy. Astr. Soc. Monthly Notices*, **79**, 343 (1919).

[2] *A. P. J.*, **49**, 137 (1919).

[3] *Ibid.*, **49**, 343 (1919).

[4] *Ibid.*, **41**, 400 (1915); **46**, 1 (1917).

[5] *Ibid.*, **44**, 137 (1916).

[6] *P. Z.*, **21**, 361 (1920).

or more caused an increase in the photo-electric current, a change amounting to as much as 60 per cent being observed as the current was altered from 1 to 3 amperes. The effects showed considerable time lag, thus the equilibrium value of the photo-electric current was not obtained until more than an hour had elapsed after the current through the bismuth had been maintained at a steady value. Control experiments showed that the heat effect and the magnetic effect of the current were not responsible for the increase in the photo-electric current. (The effects persisted after the current through the bismuth was stopped, fatigue, however, setting in and reducing it.) A similar, but much smaller, effect was obtained with zinc.

CHAPTER V

THE PHOTO-ELECTRIC EFFECT AS A FUNCTION OF THE FREQUENCY AND STATE OF POLARIZATION OF THE LIGHT

RICHARDSON'S STATISTICAL THEORY

A number of investigations on the photo-electric effect as a function of the frequency of the light have been carried out. The only theoretical expressions for this function are those due to O. W. Richardson.[1] They are deduced along the following lines. Consider a cavity in a piece of matter, containing an atmosphere of electrons in equilibrium, so that just as many enter the matter through the surface as leave it. Richardson finds, by applying the usual methods of the kinetic theory of gases, that the number of electrons impinging on a unit area of the surface from the atmosphere is

$$N_1 = AT^2 e^{-\frac{w_0}{RT}} \qquad (1)$$

where A is a constant, T the temperature, R the gas constant for a single molecule, and w_0 the work done by the electron against the forces tending to retain it in the matter. The number of electrons leaving the surface, on the other hand, is assumed to be determined by the total radiation (acting photo-electrically) which is in equilibrium with the matter at that temperature and, therefore, traversing it in all directions. The energy density of the radiation between the frequencies ν and $\nu + d\nu$ is

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[1] *P. M.*, **23**, 594 (1912); **24**, 574 (1912); **27**, 476 (1914).

$$E(\nu, T)d\nu$$

where $E(\nu, T)$ is some function of ν and T (such as Planck's or Wien's). The rate of absorption of this energy is

$$\frac{c}{4}\,\epsilon E(\nu, T)d\nu$$

where c is the velocity of light and ϵ the emissivity. Let $F(\nu)$ be the number of electrons emitted per unit area of the surface when radiation of frequency ν passes through it. Consequently, the total number of electrons emitted in unit time is

$$N_2 = \frac{c}{4}\int_0^\infty \epsilon F(\nu)E(\nu, T)d\nu \qquad (2)$$

In his earlier papers Richardson used Wien's formula

$$E(\nu, T) = \frac{8\pi}{c^3}\,h\nu^3 e^{-\frac{h\nu}{RT}}$$

while in the last paper Planck's formula was used

$$E(\nu, T) = \frac{8\pi}{c^3}\,\frac{h\nu^3}{e^{-\frac{h\nu}{RT}} - 1}$$

When there is equilibrium, the value of N_1 (equation (1)) must equal N_2 (equation (2)). The equations to be satisfied are

$$\frac{c}{4}\,\frac{8\pi}{c^3}\int_0^\infty \epsilon F(\nu)h\nu^3 e^{-\frac{h\nu}{RT}}d\nu = AT^2 e^{-\frac{w_0}{RT}} \qquad (3)$$

or

$$\frac{c}{4}\,\frac{8\pi}{c^3}\int_0^\infty \epsilon F(\nu)\,\frac{h\nu^3}{e^{-\frac{h\nu}{RT}} - 1}\,d\nu = AT^2 e^{-\frac{w_0}{RT}} \qquad (4)$$

according to whether Wien's or Planck's expression is adopted. A solution of (3) is

$$\epsilon F(\nu) = 0 \qquad \text{when } 0<h\nu<w_0\ .$$

$$\epsilon F(\nu) = \frac{Ah}{R^2\nu^2}\left(1 - \frac{w_0}{h\nu}\right) \qquad \text{when } w_0<h\nu<\infty \qquad (5)$$

$w_0 = h\nu_0$, where ν_0 is the frequency of the photo-electric threshold. Should (4) be considered instead of (3) the value of the function F (ν) above the photo-electric threshold takes a slightly different form, viz.,

$$\epsilon F(\nu) = \frac{Ah}{R^2\nu^2}\left(1 - e^{-\frac{h\nu}{RT}}\right)\left(1 - \frac{w_0}{h\nu}\right)$$

Returning to the solution given in equation (5) it will be seen that $\epsilon F(\nu)$ has a maximum value, which occurs when $\nu = \frac{3}{2}\nu_0$. This can be tested by experiment.

EXPERIMENTAL RESULTS

Richardson points out that the photo-electric experiments are carried out under conditions different from those stipulated in the theoretical discussion. Experimentally we have to deal with the rate of emission of photo-electrons under given illumination and not with a state of equilibrium as was assumed in the theoretical discussion when the matter was supposed to be traversed by isotropic radiation. Also, the functions given above are solutions of the equations, but not necessarily complete solutions. The solutions imply that the function has the same shape for all substances, the nature of the substance only enters by fixing ν_0, the frequency of the photo-electric threshold.

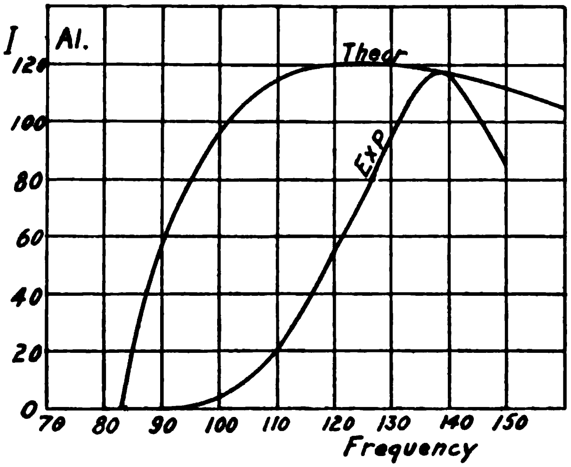

FIG. 7.

Compton and Richardson[1] investigated the photo-electric sensitivity of Pt, Al, Na and Cs with monochromatic light of different frequencies to test the expression given in (5). The results for Al and Na are shown in the accompanying figures. For both Al and Na, there is a definite maximum sensitivity which, however, is much more sharply defined than the theoretical maximum. Its position is in accordance with the predictions of the theory.

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[1] *P. M.*, 26, 549 (1913).

It will be noticed that Na has *two* well defined maxima. The shape of the experimental curves differs considerably from that given by the theory. The available ultraviolet region is so limited that no second maximum could be looked for with Al, nor could the curve be carried as far as the first maximum for Pt. In a later paper, Richardson and Rogers[1] reduce these experimental results to absolute values which are expressed in coulombs per calorie.

Richardson[2] went into the question of whether it was possible to explain thermionic emission of electrons by a photo-electric emission due to the radiation from the hot body illuminating itself (an "autophoto-electric" effect). He found, on thermodynamical assumptions, that the photo-electric current from a substance when illuminated by full radiation characteristic of a temperature, T, should have the form

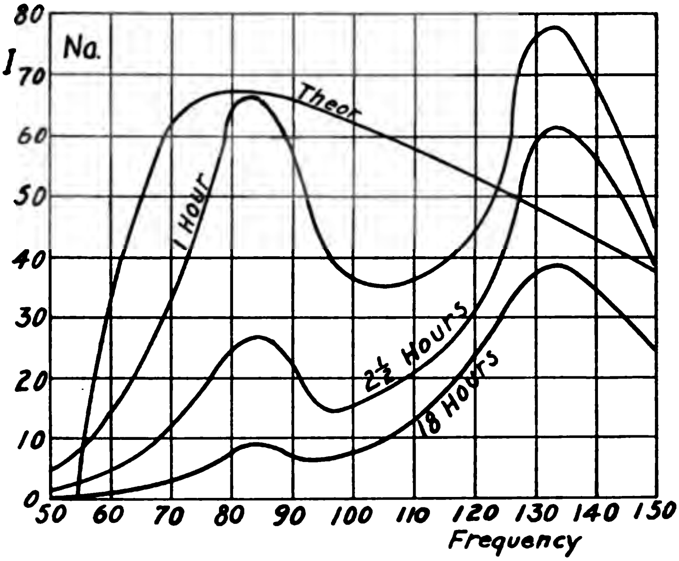

FIG. 8.

$$i = AT^2 e^{-\frac{\varphi}{kT}}$$

This equation is identical with that for the ordinary thermionic emission. W. Wilson[3] found that the photo-electric current from sodium potassium alloy obeyed this law as the temperature T of the source of light was varied. (The source was arranged so as to give approximately black body radiation.) Richardson concludes, however, that though the photo-electric current depends in the same way on the temperature as the thermionic emission, the photo-electric current forms at the best but a very insignificant fraction of the thermionic current. Langmuir[1] mentions that the magnitude of the photo-electric current produced by radiation from an incandescent filament was only one-millionth part of the thermionic current from the filament. A deposit of tungsten was formed on the inside of a bulb by evaporation from a tungsten filament at the center, and a photo-electric current from the deposit was obtained on making the filament incandescent.

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[1] *P. M.*, 29, 618 (1915).

[2] "Emission of Electricity from Hot Bodies," p. 101.

[3] *P. R. S.*, 93, 359 (1917).

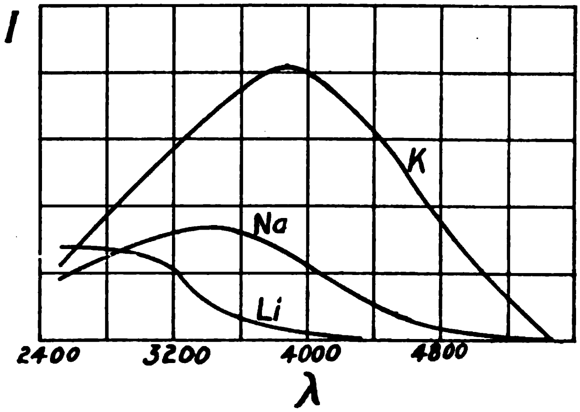

FIG. 9.

Souder[2] carried out a number of investigations on K, Na and Li. In Compton and Richardson's experiments, the Na surface was prepared by distillation, while in his experiments the surface was produced by cutting in vacuo. The results are shown in fig. 9. It will be noticed that there is no evidence of a second maximum in Souder's experiments, as would be expected from Compton and Richardson's experiments.

In any attempt to build up a theoretical formula for the photo-electric sensitivity of a substance, it will be seen that any effort to check it accurately by experiment will be subject to serious difficulties. The number of electrons which emerge from a surface in any photo-electric experiment will be a complicated function of the distance to which the light penetrates into the surface and of the absorption coefficient of the photo-electrons by the substance. Hence, the photo-electric sensitivity, as obtained in the experiments quoted, is subject to unknown corrections before what may be called the true photo-electric sensitivity can be obtained. In this connection, reference may be made to a paper by O. W. Richardson.[1]

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[1] *J. A. C. S.*, **42**, 2190 (1920).

[2] *P. R.*, **8**, 310 (1916).

NORMAL AND SELECTIVE EFFECTS

One of the most puzzling phenomena in the photo-electric effect is the so-called "selective photo-electric effect," which appears in some cases. According to the careful experiments of Pohl[2] the photo-electric current per unit of energy absorbed from the light is, in general, independent of the angle of incidence and also of the state of polarization of the incident beam. In certain cases (the alkali metals), however, there is a remarkable departure from this rule, the photo-electric current being many times stronger when the electric vector in the light beam has a component perpendicular to the surface than when it is wholly parallel to the surface. This effect, the "selective" effect, is restricted to a range of wave-lengths characteristic of the metal, while the "normal" effect has no such restriction. A typical diagram of the effect is shown in fig. 10, where $E\parallel$ and $E\perp$ denote the relation of the electric vector to the plane of incidence. Pohl and Pringsheim have obtained a large mass of experimental data as to these effects, which is summarized in the writer's "Photo-Electricity." No satisfactory explanation has yet been given of the phenomena.

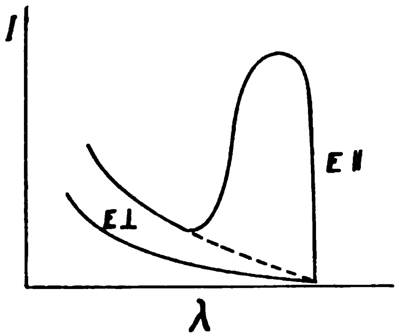

Fig. 10.

With unpolarized light, the two effects are superposed showing a well-marked maximum coinciding with the maximum of the selective effect. In the earlier investigations, it was generally assumed that a pronounced maximum in the photo-electric current curve, when the substance was illuminated by light of different wave-lengths, indicated a selective effect. While this is no doubt true in the case of the alkali metals, many recent investigations show a maximum in the photo-electric current curves plotted against wave-lengths when a selective effect does not exist. The theoretical investigations of Richardson, already referred to, point to a maximum photo-electric current at a certain wave-length, without any reference to the state of polarization of the light, or to the inclination of the beam. It is, therefore, advisable to restrict the term "selective effect" to the narrow limits originally suggested by Pohl and Pringsheim. It should be kept for that occasion when, reckoned for equal amounts of absorbed light, the photo-electric sensitivity is abnormally large when the electric vector in the light beam has a component perpendicular to the surface, as compared to the case when it is entirely parallel to it. A criterion equivalent to this, which in some cases may be more convenient to employ, is an accentuation of the maximum as the angle of incidence is increased. An illustration of this may be taken from Pohl and Pringsheim's work. Na-K alloy and Ca both show a maximum (which is, however, much less pronounced in the case of Ca) in the photo-electric current curves when unpolarized light is used. However, as the angle of incidence is increased, the maximum becomes more and more pronounced in the case of Na-K alloy, but in the case of Ca, it becomes less and finally vanishes. A direct test with polarized light shows that Ca does not possess a selective effect, while Na-K alloy does. It is evident, then, that something more than the mere presence of a maximum in the photo-electric current curves when plotted against the wave-length, is necessary to determine whether a real selective effect is present. It may be remarked that Pohl and Pringsheim assumed that Li had a selective effect because of the presence of a maximum at λ 2800, when illuminated by unpolarized light, on the analogy of the maxima obtained for the other alkali metals, for most of which the existence of the selective effect had been directly demonstrated with polarized light. Had they worked on Li, after discovering that the maximum in the case of Ca did not necessarily imply a selective effect, they would no doubt have made further tests using polarized light.

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[1] *P. M.*, 31, 149 (1916).

[2] *V. d. D. P. G.*, 10, 339, 609, 715 (1909).

Millikan and Souder[1] investigated the photo-electric current from a sodium surface as a function of the wave-length of light using perpendicular incidence. They found a maximum sensitivity at the same wave-length as that at which Pohl and Pringsheim located the maximum of the selective effect. They also found that the magnitude of the maximum depended very much upon the age of the surface, indeed, for very new surfaces the maximum could scarcely be detected. They are inclined to regard the selective effect as merely the normal effect in the neighborhood of an absorption band, *i. e.*, where one particular frequency predominates.

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[1] *N. A. S. P.*, **2**, 19 (1916); *P. R.*, **8**, 310 (1916).

The maximum velocities of the electrons in the region where the selective effect is most marked fall in with Einstein's quantum relation exactly as they do in regions where only the normal effect exists, a result verified by Millikan's accurate experiments on Na and Li in the determination of "*h*."

Hughes[1] found that there was a small difference in the distribution of the electrons emitted in the selective effect as compared with that of those emitted in the normal effect. This difference, however, was quite small compared with the difference between the total currents for the two effects. The difference in the distribution could be attributed to a difference in the *direction* distribution, or to a difference in the *velocity* distribution of the photo-electrons, that is, the effects could be explained by assuming that in the selective effect the photo-electrons were somewhat more crowded towards the perpendicular to the surface, or that they were, on the whole, slower than in the normal effect. In a later paper[2] it was shown that a difference in the direction distribution existed, the photo-electrons in the selective effect being emitted, on the whole, in directions nearer to the perpendicular to the surface than in the normal effect.

If, over the region in which the selective effect existed, one found that the light polarized in the $E\|$ plane were absorbed in a much thinner layer of the surface than light polarized in the $E\perp$ plane, one would have a natural explanation for the existence of the selective effect. According to Pohl and Pringsheim[3] the position of the selective effect is that in which the reflecting power is exceptionally high, and high reflecting power, on optical theory, goes with rapid absorption. They did not investigate whether the reflecting power in the region of the selective effect differed markedly for beams polarized in the two principal planes. Recently, some experiments on this point have been carried on by Miss Mabel Frehafer,[1] who investigated the reflection and absorption of light by K and Na. The ratios of the reflecting powers of Na and K surfaces for light polarized in the two principal planes are shown in fig. 11. It will be seen that for both Na and K, a remarkable variation in the ratio takes place in the ultraviolet. For Na, the minimum in the curves is approximately near the position of the selective maximum. Any association between the two is made doubtful, however, by the fact that no such association appears for K. Experiments were carried out on the transparency of thin films of K and Na, but no specially marked effects were noted in the selective region.

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[1] *P. M.*, 31, 100 (1916).

[2] *P. R.*, 10, 490 (1917).

[3] *V. d. D. P. G.*, 15, 173 (1913).

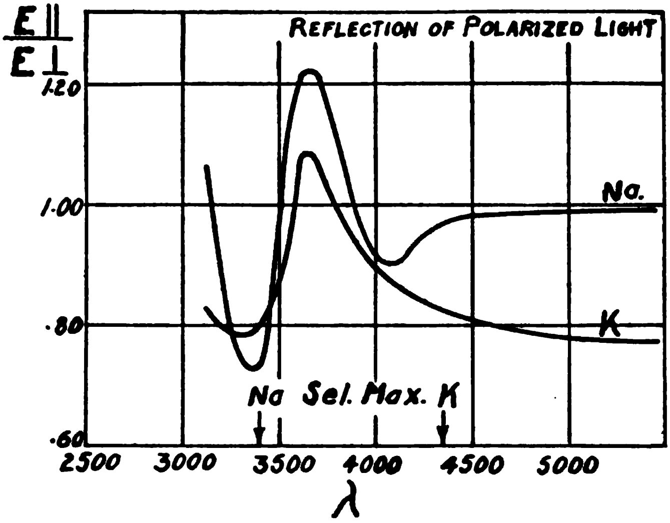

Fig. 11.

Should further experiments show definitely that no explanation of the selective effect in terms of unequal absorption of the beams polarized in the two principal planes is possible, it will be necessary to look elsewhere for an explanation. Possibly there are systems in the alkali metals so orientated that they are more easily broken up by light which has a component of electric force perpendicular to the surface than when the electric force is entirely parallel to it. So far as energy relations go, the selective effect appears to be governed by the quantum relation, just as is the normal effect.

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[1] *P. R.*, 15, 110 (1920).

CHAPTER VI

PHOTO-ELECTRIC PROPERTIES OF THIN FILMS

Certain investigations recorded in the writer's "Photo-Electricity" implied that the photo-electrons from thin films had necessarily high emission velocities. Stuhlmann and Compton[1] found that there was no departure from Einstein's law, provided adequate care was taken to prevent the formation of charged layers, apparently due to thin films of oil or grease forming on the surfaces investigated. They also found that the photo-electric effect of sputtered platinum was greater than that of ordinary platinum.

Stuhlmann[2] took up the question of the maximum velocities of photo-electrons emitted from thin films of Pt on quartz plates. He confirmed Robinson's result that the maximum emission energy of the photo-electrons was about 40 per cent greater when they left the *emergence* side than when they left the *incidence* side. At the time these experiments were carried out, the investigations of the emission energies of photo-electrons from ordinary surfaces (*i. e.*, from the *incidence* side) all led to values of "*h*" about 10 per cent to 20 per cent too low, and it was suggested therefore, as a result of these velocity measurements on thin films, that the correct value for "*h*" might be obtained, provided that the velocities were measured for the *emergence* side. In view of Millikan's proof that "*h*" can be obtained accurately from experiments on the velocities of photo-electrons from the *incidence* side, this explanation falls to the ground, and indeed renders it exceedingly doubtful whether the photo-electrons can possibly have a greater maximum energy on the *emergence* side. The differences in the velocities are probably spurious, though it is difficult to say where the experimental arrangements are faulty.

Robinson[3] measured the photo-electric effect per unit light energy absorbed for thin films as a function of the thickness. The curves had very sharply marked maxima at thicknesses of about 10^{-7} cm.

In 1919, two independent investigations of a more elaborate type than any of the previous investigations on thin films were published. The results differ in several respects. Stuhlmann[4] produced his thin films by a novel method. They were obtained by the evaporation in vacuo from a wire, made white-hot, and placed to one side of a plate of quartz. Thus a deposit of decreasing thickness was obtained on the quartz and the photo-electric effect of any thickness could be studied by directing the light on to the proper part of the deposit. The metals investigated were Pt and Ag. The results for Pt are reproduced in the diagram. It will be seen that the thickness for which the photo-electric current is a maximum decreases with the frequency. Since all the curves cut the abscissa at the origin at a finite angle, the tangent here may be taken to measure the photo-electric effect per unit thickness unaffected by any question as to absorption of light or of electrons in the film. Stuhlmann concludes that for very small thicknesses (7×10^{-7} cm.) the electrons pass through the film colliding according to Rutherford's hypothesis of "single scattering" and little or no energy is lost by the electron. For thicker films, ordinary "compound scattering" comes into play, in which the electrons lose energy, and for still thicker films true absorption of photo-electrons takes place. By comparison of the results for Pt and for Ag, it was concluded that the stopping power of a metal for photo-electrons increases as the energy of the electron increases up to a certain limiting value, and is greater, the heavier the atom.

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[1] *P. R.*, **2**, 199 (1913); **2**, 327 (1913).

[2] *Ibid.*, **3**, 195 (1914).

[3] *P. M.*, **32**, 421 (1916).

[4] *P. R.*, **13**, 109 (1919).

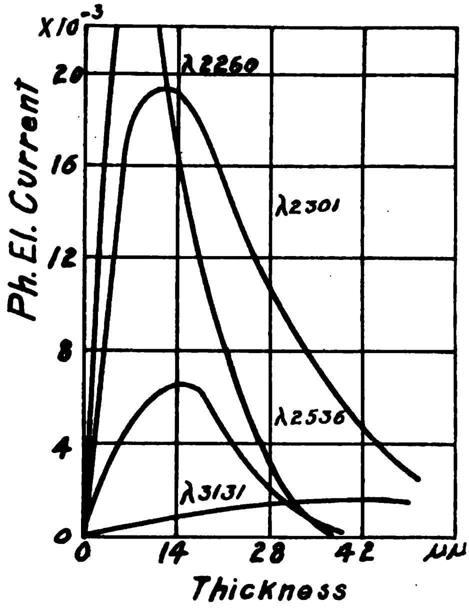

FIG. 12.

Compton and Ross[1] investigated Pt and Au films produced by sputtering. It may be useful to record that three entirely different methods were used for measuring the thicknesses of the films and gave results in very good agreement. The form of the function giving the relation between the photo-electric effect and the thickness was deduced from three different sets of assumptions.

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[1] *P. R.*, 13, 374 (1919).

These were as follows: (1) That the number of the photo-electrons which retain ability to escape falls off exponentially with the distance moved through perpendicularly to the surface; (2) that the number which retain ability to escape falls off exponentially with the distance moved through in any direction; and (3) that an electron loses energy in proportion to the distance moved through the metal. The thickness of the film giving the maximum photo-electric effect was determined theoretically for each case and compared with the experimental results. The results were found to fit either hypothesis (1) or hypothesis (2), but would not fit hypothesis (3) at all. (2) is probably more plausible than (1), as the electrons are as likely to start off in any one direction as in any other. One set of curves is reproduced here. The results differ radically from those of Stuhlmann. In the first place, they possess two maxima. The second maximum (the one for the greater thickness) was found to disappear in the course of time, and seems to be associated with the unstable form of newly sputtered Pt. The single maximum in Stuhlmann's work would imply that the film produced by evaporation did not pass through the temporary state of instability. The maxima in Compton and Ross's work occur at about 4 × 10^{-7} cm. for λ 2536 and about 2.5 × 10^{-7} cm. for λ 2100 and λ 2225, while in Stuhlmann's work the maxima are at about 15 × 10^{-7} cm. for λ 2536, and about 12 × 10^{-7} cm. for λ 2260. Since the experiments are in agree-

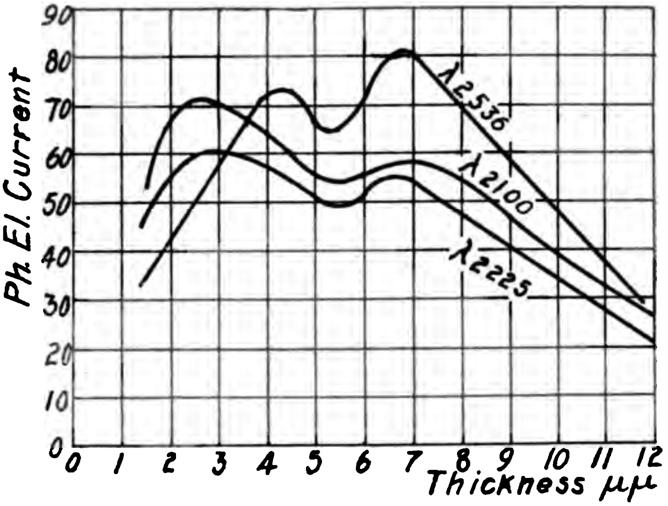

FIG. 13.

ment with the view that the ability to escape decreases exponentially with the distance travelled, the average distance through which an electron can travel (a sort of mean free path) may be calculated. The values are 2.67×10^{-7} for Pt, and 5.0×10^{-7} for Au, which are greater than, but of the same order of magnitude as, the distance between the atomic centers in these metals. The most important result of this investigation perhaps is that the ability to escape is the same for a fast photo-electron (*i. e.*, one produced by the shortest wave-length) as for a slow photo-electron. This can only be accounted for on the view that a photo-electron loses its energy completely at a single collision, and not gradually during a succession of collisions, for in the latter case it is obvious that the faster electron would travel further. A similar conclusion may be drawn from Stuhlmann's work, although in his experiments the "mean free path" of an electron in the metal appears to be greater than indicated by the work of Compton and Ross.

CHAPTER VII

PHOTO-ELECTRIC EFFECTS OF NON-METALLIC ELEMENTS AND INORGANIC COMPOUNDS

Dima[1] investigated the photo-electric effect of numerous inorganic compounds. These were in the form of capsules of compressed powder. The light used was that from a quartz mercury lamp, unresolved. As the substances showed fatigue in widely varying amounts, the *initial* values of the photo-electric effect were taken so as to make a fair comparison. The values of the initial photo-electric current obtained from the various compounds under similar conditions are as follows:

HgI_2	10	HgI	112	CuO	4800	Cu_2O	14400
$HgCl_2$	2	$HgCl$	12	$CuCl_2$	10	$CuCl$	50000
HgO	70	Hg_2O	280	PbO_2	1700	PbO	3200
$Hg(C_6H_5CO_2)_2$	12	$Hg(C_6H_5CO_2)$	18	CrO_3	1	Cr_2O_3	50
SnO_2	24	SnO	1220	BiO_3	70	Bi_2O_3	110
SnS_2	186	SnS	1440	MnO_2	48	Mn_3O_4	130
Fe_2O_3	202	FeO	7200			MnO	500
$FeCl_3$	1	$FeCl_2$	26				

It is evident from the table that when a metal can combine with another element in two ways, that compound in which the metal has the lower valency has the bigger photo-electric effect.

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[1] *C. R.*, **176**, 1366 (1913); **177**, 590 (1913).

This view was verified by experiments on the photo-electric effects of MnO, Mn_3O_4, Mn_2O_3, MnO_2, which were 400, 240, 176 and 37, respectively. It was noticed that the photo-electric fatigue was always greater in a compound in which the metal has a low valency (*i. e.*, in the one with the bigger photo-electric effect) than in the corresponding compound in which it has a higher valency. Thus, the photo-electric effect of PbO decreased by 60 per cent in twenty minutes, while that of PbO_2 remained constant for a period of over three hours. It is probable that the fatigue is associated with the conversion of the surface of the compound, by illumination, into the more stable compound in which the metal has a higher valency and whose photo-electric effect is smaller. In a few cases, *e. g.*, molybdenum trioxide, the photo-electric effect increased with continued illumination. Dima suggested that the light effected a chemical reduction in such cases. The following results were obtained for a number of halides:

	Chloride	Bromide	Iodide
K	67	320	1200
Pb	31	97	3000
Hg (—ous)	15	19	1400
Hg (— ic)	5	14	230
Ag	200	430	750
Cd	60	24	18

With the single exception of the compounds of Cd, it will be seen that the photo-electric effect increases as a heavier halogen atom is substituted for a lighter.

Naccari[1] investigated the effect of light on the transmission of electricity through toluene between a plate and a gauze 1 mm. in front of it. The fact that the increased conductivity due to illumination was independent of the direction of the field seemed to indicate that a volume ionization was produced in the liquid rather than a surface effect at the electrodes.

La Rosa and Cavallaro[2] investigated the effect of illumination on the transmission of electricity through a number of liquids. Surface effects and volume effects were generally superposed in varying proportions. Thus, in water, alcohol and acetic ether, the surface effect predominated, while in ethyl ether and methylene bromide, the volume effect predominated.

[1] *N. Cimento*, **4**, 232 (1912).

[2] *Ibid.*, **6**, 39 (1913).

Kelly[1] employed a method particularly suited to the study of the photo-electric effect of insulators. The insulator was atomized in liquid form (either molten or in a solution), and then passed into an apparatus of the type used by Millikan in his determination of "*e*." The behavior of one of the particles so produced was studied when in between the plates of the condenser. The particle, when initially charged, as was almost always the case, could be held at rest by an electric field acting in opposition to gravity. If, now, a beam of ultraviolet light were passed into the apparatus, the loss of photo-electrons by the particle would alter its charge and destroy the equilibrium. Just as in Millikan's work on "*e*," the charge lost could be measured. It was found that with sufficiently low light intensities, the emission of electricity from the particles consisted in the emission of electrons one by one. There is no reason to suppose that this does not hold with greater intensities of light, though it is difficult to demonstrate that this is so when the electrons are emitted copiously. The method was used to determine the photo-electric thresholds for insulators. They are as follows: Sulphur $< \lambda$ 2400, $> \lambda$ 2200. Shellac $< \lambda$ 2200. Oil and Paraffin $< \lambda$ 2150.

CHAPTER VIII

PHOTO-ELECTRIC EFFECTS OF DYES, FLUORESCENT AND PHOSPHORESCENT SUBSTANCES

The only recent work to be recorded in this chapter is that due to Schmidt.[2] He investigated the effect of light on the "phosphor" CaBiNa. In the dark this is a dielectric, under the influence of light it becomes conducting. When a sufficiently thin layer is used, so that the light can penetrate throughout the material down to the metal which acts as its support, a current can be passed through it when illuminated. This is known as the actinodielectric effect. The curve connecting the conductivity with the frequency of the light had a maximum at λ 5800 and a minimum at λ 4300 (thickness used .01 mm.). If thick layers are used (*e. g.*, .5 mm.) several maxima are obtained. These are determined more by the absorption characteristics of the substances than by the actinodielectric properties, hence the necessity for thin films.

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[1] *P. R.*, **16**, 260 (1920).

[2] *A. d. P.*, **44**, 477 (1914).

Compton and Smyth[1] have shown that fluorescing iodine vapor is more easily ionized than non-fluorescing iodine vapor. Further mention of this paper will be found in the chapter on ionizing potentials.

CHAPTER IX

POSITIVE RAYS PRODUCED BY LIGHT

No further work appears to have been done on this subject. It seems worth while to examine the matter more thoroughly and to determine the nature of the positive carriers should their existence be verified.

CHAPTER X

SOURCES OF LIGHT USED IN PHOTO-ELECTRIC EXPERIMENTS

Among reliable sources of ultraviolet light which have come into regular use in photo-electric work since 1913 may be mentioned the Cooper Hewitt quartz mercury lamp. For constant illumination, such sources are very satisfactory. The shortest wave-length available is λ 1849, owing to the absorption of the quartz. Considerably shorter wave-lengths can be obtained from arcs between metals in vacuo and from discharges in gases. Lyman[2] has investigated the extent into the ultraviolet of the spectrum of a discharge through helium and hydrogen and other gases. The hydrogen spectrum ends at about λ 905, and the helium spectrum at about λ 510. Similar results were obtained by a different method by Richardson and Bazzoni. Lyman also investigated the spectra of sparks between various metals in his vacuum spectroscope. In no case did he get the spectrum to extend beyond about λ 2000. McLennan and Lang[3] investigated the extent of the spectrum emitted from arcs of various metals. The Hg, Fe and Cu spectra extended to λ 1435, λ 1427, and λ 1925, respectively. Carbon showed a much shorter line, viz., λ 584.

Millikan and Sawyer[4] found that sparks between metallic electrodes very close together in an extremely good vacuum gave spectra extending far into the ultraviolet. With electrodes of C, Zn, Fe, Ag and Ni, the respective spectra extend to λ 360.5, λ 317.3, λ 271.6, λ 260.0, λ 202.0.

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[1] *Science*, **51**, 571 (1920).

[2] "The Spectroscopy of the Extreme Ultra-Violet," Longmans; also *A. P. J.*, **43**, 89 (1916); *Science*, **45**, 187 (1917).

[3] *P. R. S.*, **95**, 258 (1919).

[4] *P. R.*, **12**, 167 (1918); *A. P. J.*, **52**, 47 (1920).

If one wishes to carry out photo-electric experiments with monochromatic light of wave-lengths below about λ 1850, some type of vacuum spectrometer of the kind used in the investigations just cited must be used. Sabine investigated the velocities of photo-electrons by very short wave-lengths isolated in a vacuum spectrometer. Such experiments are very troublesome to carry out on account of the necessity of having the source of light, the grating, and the apparatus containing the illuminated electrode, all in the same vacuum.

The monochromatic illuminator made by Hilger is useful for isolating any portion of the spectrum from the visible to λ 1850. The light which passes through is not absolutely monochromatic on account of a small amount of unavoidable scattering of light by the lenses and the interior. In some special cases, it has been found advisable to use light filters to help to cut out all the light except that of the particular wave-length desired.

For many purposes, where an extremely narrow range of wave-lengths is not required, light filters may advantageously take the place of a monochromatic illuminator in the visible region. A greater intensity of light is usually available than with the instrument. In addition to the list of light filters given in the writer's "Photo-Electricity" may be mentioned the numerous light filters put out by the Eastman Company. Being made of gelatine or colored glass, they are much more convenient than solutions. One series of filters is particularly adapted for use with the mercury lamp, the range of transparency not including more than one or two lines, and so practically giving monochromatic light. (A filter is made for use with the green line of mercury λ 5467 which transmits about 50 per cent of this and is quite opaque to all the rest of the mercury spectrum.) It is unfortunate that a similar series of light filters has not as yet been produced for use in the ultraviolet. The Eastman series includes one ultraviolet filter.

Methyl alcohol has a sharply defined absorption band beginning at λ 2350 according to Hagenow.[1] Kelly[2] found that cobalt chloride, dissolved in methyl alcohol, had a fairly well-defined transmission region in the ultraviolet from λ 2650 to λ 4600 for a path 8 mm. long through a 2-normal solution. The lower limit was extended to λ 2400 for a .01 normal solution.

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[1] *P. R.*, 13, 415 (1919).

[2] *Ibid.*, 16, 260 (1920).

Information as to new substances available for use as "windows" in photo-electric work has been obtained recently by Miss Laird.[1] Silver foil .00002 cm. thick transmitted fairly well down to λ 1140, and faintly to λ 900. Celluloid films (.02 mg./cm.^{2}) transmitted easily to λ 900 and faintly to λ 600, and there was no direct indication of a lower limit.

Miethe and Stenger[2] give a list of the transparency regions in the ultraviolet for solutions of tartrazine, filter yellow, Martin's yellow, fluorescin, eosin, and nitrosodimethylaniline. The short wave-length limits of these substances range from about λ 3200 to about λ 2600. Several of them give narrow transmission regions when concentrated, *e. g.*, tartrazine transmits a band from λ 3000 to λ 3080.

Lewis[3] finds that benzol transmits down to λ 1900.

CHAPTER XI

IONIZING AND RADIATING POTENTIALS

EXPERIMENTAL METHODS

Most of the phenomena of photo-electricity, as hitherto considered, deal with the separation of electricity, when matter in some form or another is illuminated by light of a suitable kind. The inverse effect, the production of light by the passage of electricity through matter, is a vast subject, including the whole field of spectroscopy, and will not be considered here. However, there is one part which is so intimately connected with photo-electricity (in its ordinary connotation) and which brings out the quantum relations similar to those underlying photo-electricity so clearly that it is natural to include it here. That part is usually designated as the subject of ionizing and radiating potentials. A remarkable advance has been made in our knowledge in the subject during the past two or three years.

When a molecule is struck by a moving electron, the collision may, or may not, be an elastic one. By an elastic collision is meant one in which the electron rebounds with a negligible transfer of energy. (If the mass of the molecule were infinite compared with that of the electron, there would be no transfer of energy.) If there is a transfer of energy to a monatomic molecule, there may be complete ionization as shown by the production of positive and negative ions, or there may be "partial ionization," *i. e.*, a disturbance of the atom, which is not detectable as ionization but is shown by the production of radiation. In the cases of polyatomic molecules, collisions are more or less inelastic, the transferred energy presumably being used up in increased motion of the component atoms relative to each other.[1]

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[1] *P. R.*, 15, 543 (1920).

[2] *Zeits. Wiss. Phot.*, 19, 57 (1919); *Sc. Abs.*, 1920, 981.

[3] *P. R.*, 16, 367 (1920).

The ionizing potential is the least potential through which an electron, starting from rest, must fall, to acquire sufficient kinetic energy to enable it to ionize a normal molecule on impact. Similarly a radiating potential measures the least kinetic energy which an electron must have, so that, on impact with a molecule, it may emit a monochromatic radiation characteristic of the molecule. (It is generally agreed that the radiation occurs afterwards as the molecule returns to its normal state.) There may be several radiating and ionizing potentials depending on the type of ionization and radiation produced. Energy in excess of that corresponding to the critical potential is a necessary, but by no means a sufficient, condition that ionization or radiation may occur. There are two principal ways of measuring the ionizing and radiating potentials. The "total and partial current" method is as follows.

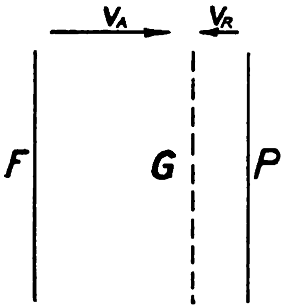

FIG. 14.

Let F (fig. 14) be a source of electrons (generally an incandescent filament), G a gauze, and P a plate, in a gas at a suitable pressure, generally between 1 mm. and .01 mm. If the total current to the gauze and plate combined be measured as a function of the accelerating potential V_A, the curve will be a smooth curve up to a certain point, where its slope will increase abruptly (fig. 15). This indicates that the electrons from F have acquired sufficient energy from the electric field to ionize some of the molecules with which they collide. If now it is arranged so that there is a small field, V_R, between the gauze and the plate, retarding the electrons passing through the gauze, the current to the plate is called the partial current. Now as long as the collisions are elastic, the electrons in their journey from F to G will acquire kinetic energy determined by their position in the field. Hence, the current received by P will, in general, remain constant or increase regularly as the accelerating potential is increased. If, however, the electrons are accelerated until they make inelastic collisions, then those which get through the gauze will have a smaller velocity than before, and so the field V_R is able to stop a greater proportion than before inelastic collisions set in. The dips in the curves then tell us when inelastic collisions take place. When the gas pressure is high enough to ensure that most electrons make several collisions between F and G (fig. 16), then a dip will occur, under suitable conditions, at every multiple of the value of the critical potential. Collisions are, of course, inelastic when ionization takes place, for there is a transfer of energy to effect the ionization. If an inelastic collision is indicated by the partial current method, but no ionization is indicated by the total current method, it is concluded that at this point radiation sets in. This is inferred from the good agreement between experiments of this kind and those showing directly the presence of radiation. Hence, when it is convenient to use the "total and partial" current method, one may infer radiation from the dips in the partial current curves. The use of the partial current curves is due to Franck and Hertz.[1] It is, of course, possible that other phenomena (*e. g.*, dissociation) besides radiation may be accompanied by inelastic collisions. Should there be

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[1] Compton and Benade, *P. R.*, **8**, 449 (1916).

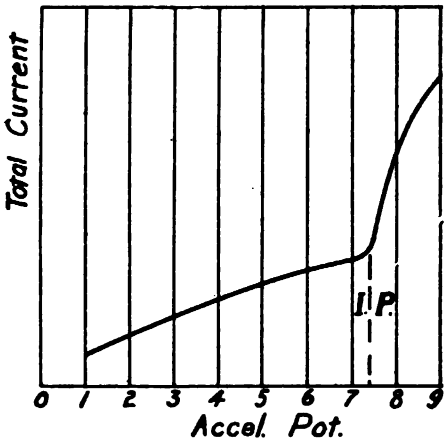

FIG. 15.

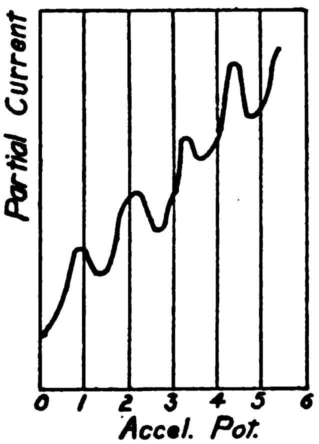

FIG. 16.

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[1] *V. d. D. P. G.*, 16, 10 (1914).

two radiating potentials, as in the case of mercury (4.9 and 6.7 volts corresponding to λ 2536 and λ 1849), it may well be that the "total and partial" method and the more direct methods do not show up the two critical points equally well.

The Lenard method is to accelerate electrons from a source, F, to a gauze, G, after which they pass into a retarding field, V_R, which is greater than V_A, so that no electrons get across to P (fig. 17). If the electrons on passing through G have acquired sufficient energy to ionize molecules after passing through the gauze, the positive ions so produced are driven into P. The method then consists in noticing (usually by a sensitive electrometer) the point at which positive ions can be detected as V_A is increased. Inasmuch as this method marks the ionizing potential by noting the beginning of a current of positive ions, while the total current method marks it by an increase in a negative current already existing, it should, in general, be the more sensitive method. This method, which was the one principally used in earlier investigations, did not distinguish between the ionizing potential and the radiating potential, for the radiation falling on P would produce a photo-electric effect at P and so cause it to emit photo-electrons, leaving it charged positively, which, of course, is exactly what happens when positive ions are driven to it. Davis and Goucher[1] introduced a method whereby the ionizing potential and radiating potential could be separated. A second gauze, G′, was introduced as shown (fig. 18) so that a small field, V_1 sufficient, if properly directed, to prevent the emission of photo-electrons, could be thrown on, to the right, or to the left, as one chooses. The essential

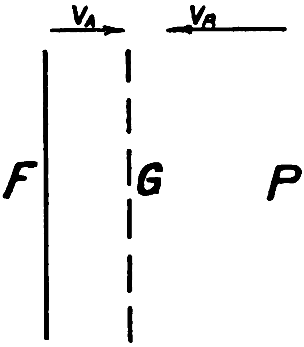

FIG. 17.

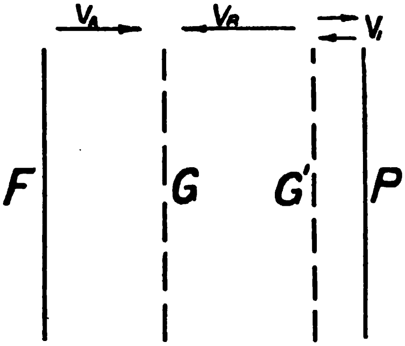

FIG. 18.

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[1] *P. R.*, 10, 101 (1917).

idea of the method is this. P can only emit photo-electrons, and, therefore, acquire a positive charge, when the field is such as to accelerate them away from it. When the field is reversed these photo-electrons cannot escape. On the other hand, the photo-electrons produced by the radiation reaching the right-hand side of the gauze G′ (by reflection or otherwise) are now enabled to pass over to P and so to give it a negative charge. Consequently, the charge acquired by P changes sign as the direction of V_1 is changed so far as radiation is concerned. Provided that the pressure is not too large, and that the difference of potential V_1 between G′ and P is considerably less than V_R, the positive ions produced between G and G′ will reach P whether the field between G′ and P helps or hinders them, for their velocity on reaching G′ is sufficient to overcome the effect of the field. Hence, the charge acquired by P does *not* change sign as the direction of V_1 is changed, so far as the positive ions are concerned. A typical curve is shown in fig. 19. The radiating potential corresponds to the point where the (I + R) and (I — R) curves diverge, while the ionizing potential corresponds to the points where there is an abrupt upward deflection in both curves.

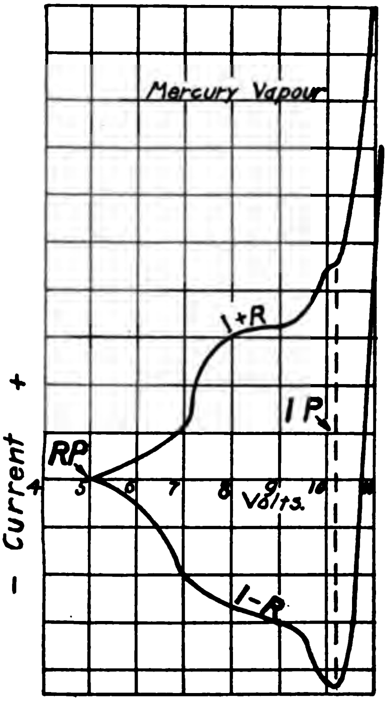

Fig. 19.

A second modification of the Lenard method, to distinguish radiating potentials and ionizing potentials is due to Compton.[1] The collecting electrode is a cylinder closed at one end by a gauze, G′, and at the other by a plate, P (fig. 20). This cylinder can be rotated about an axis as shown, so that G′ or P faces the gauze G. The essential idea of this method lies in the fact that the positive ions will contribute the same charge to the cylinder, whether the gauze end or the plate end faces the gauze G. Radiation produces a larger effect when P faces G than when G′ faces G, for in the latter case much of the radiation passes through the gauze and the photo-electrons produced inside do not escape and so contribute nothing to the charge acquired by the cylinder. Typical curves for He are shown in fig. 21. A represents the current to the cylinder (P facing G) as a function of the accelerating potential. B represents the current when G′ faces G. R is the ratio of the currents when P faces G to the case when G′ faces G. From 20 to 25 volts the ratio is constant, while from 25 volts onwards it falls rapidly corresponding to the increasing effect of ionization after the ionizing potential is passed. It should be mentioned that the constant value for R between 20 and 25 volts does not imply the absence of ionization (it implies a constant ratio between the amounts of ionization and radiation), indeed the method was devised for investigation of the ionization produced as a secondary effect of radiation under special conditions. This will be taken up again later.

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[1] *P. M.*, **40**, 553 (1920).

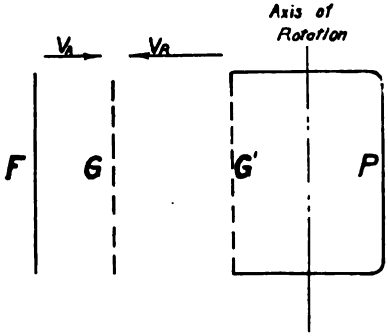

FIG. 20.

To determine the exact maximum energy of the electrons used in any determination of a critical potential, it is usual to take a "velocity distribution" curve at the same time. This is done by accelerating the electrons from F to G (figs. 14, 17, 18, 20) and measuring the number reaching P as a function of a retarding field between G and P. The difference between the applied accelerating potential and the retarding potential required to stop all the electrons gives the necessary correction to the applied potential. The more homogeneous in velocity the electron stream, the sharper are the discontinuities in the curves showing the critical potentials. To secure homogeneous electron streams, some investigators have avoided the variation

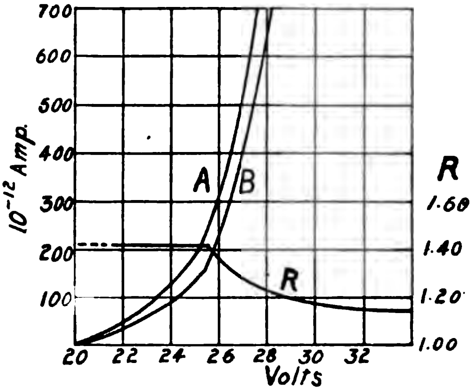

FIG. 21.

in speed arising from the fall of potential along the filament by means of a rapidly rotating commutator which cuts off the heating current when the accelerating potential is applied and vice versa. Thus the filament is an equipotential surface, while electrons are being accelerated away by the field. Other investigators (*e. g.*, Davis and Goucher) have used an equipotential platinum tube (coated with lime) heated internally by a resistance coil.

An idea of the energy distribution among the electrons as they are emitted from an incandescent filament may be obtained from the following table due to Langmuir.

	Filament temperature	
	2400° K	1200° K
90 per cent have energy exceeding	0.022 volt	0.011 volt
75 per cent have energy exceeding	0.059 volt	0.030 volt
50 per cent have energy exceeding	0.143 volt	0.071 volt
25 per cent have energy exceeding	0.29 volt	0.145 volt
10 per cent have energy exceeding	0.48 volt	0.24 volt
1 per cent has energy exceeding	0.95 volt	0.47 volt
0.1 per cent has energy exceeding	1.42 volts	0.71 volt
0.0001 per cent has energy exceeding	2.85 volts	1.45 volts

Thus, a more homogeneous stream of electrons is obtainable with a low temperature source.

If we infer the energy of the fastest electrons in an electron stream from the point where the velocity distribution curve cuts the potential axes, and assume that this energy is that of the electrons which are responsible for the first observable ionization (or radiation) the critical potentials so deduced will not be exactly correct. The reason for this is that the proportion of collisions resulting in ionization (or radiation) is very small just above a critical potential, and even if it amounted to its maximum possible value, the geometrical arrangement of the apparatus, and the fact that at low pressures the electrons do not all collide with molecules in the space where they have kinetic energy above the critical value, would prevent its full value being registered. Hence it is that the fastest electrons which are present in only just sufficient numbers to give an indication on the velocity distribution curve, cannot give a measurable ionization or radiation if the same indicating instrument be used for both measurements. This was first pointed out by Smyth[1] who worked out a method of correcting for it. For details, reference must be made to the paper. In several subsequent investigations efforts have been made to overcome the error pointed out by Smyth, but they do not in all cases appear to be adequate.

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[1] *P. R.*, 14, 409 (1919).

An exceedingly simple and accurate method of correcting for initial velocities is due to Franck and his collaborators. In the partial current curve showing inelastic collisions (fig. 16) the distance between two corresponding dips gives the exact value of the critical potential, and by comparing this with the distance between the first dip and the origin, the necessary correction to the applied potential is obtained.

COLLECTED RESULTS

The experimental results are given on the following pages. In cases where the same gas has been investigated by several observers independently, the results are given under each gas to facilitate comparison. In other cases, where a number of gases have been examined under identical conditions, it was thought advisable to collect them together, *e. g.*, the results of Foote, Mohler, and collaborators, and of Hughes and Dixon.

It should be added that in many cases, investigators have used the Lenard method and have not distinguished between the ionizing potentials and the radiating potentials. Though in many of the earlier researches, the critical potentials observed have been called ionizing potentials, in view of our recent knowledge it is possible that some of them may be radiating potentials and they are, therefore, marked with an *, unless the investigator definitely decided against radiation as an adequate explanation.

Hydrogen	*R. P.*	*I. P.*
Franck and Hertz (*V. d. D. P. G.*, **15**, 34 (1913))	11*	..
Goucher (*P. R.*, **7**, 561 (1916))	10.25*	..
Hughes and Dixon (*P. R.*, **10**, 495 (1917))	10.2*	..
Bishop (*P. R.*, **9**, 567 (1917))	11*	15.8
Davis and Goucher (*P. R.*, **10**, 101 (1917))	11	11 (*i. e.*, both at 11 volts)
	..	15.8 2nd type
	13.6	.. 2nd type
Horton and Davies (*P. R. S.*, **97**, 23 (1920))	10.5	14.4 (atom)
	13.9	16.9 (molecule)
Mohler and Foote (*J. O. S. A.*, **4**, 49 (1920);	10.4	13.3 (atom)
Bur. Stan., **1920**, 670)	12.22	16.5 (molecule)
Stead and Gossling (*P. M.*, **40**, 413 (1920))	..	15
Franck, Knipping and Krüger (*V. d. D. P. G.*, **21**, 728 (1919))	..	11.5 (molecule)

	R. P.	*I. P.*
	13.6	.. (dissociation and radiation)
	..	17.1 (dissociation and ionization)
	..	30.45 (dissociation and double ionization)
Found (*P. R.*, **16**, 41 (1920))	..	15.1
Compton and Olmstead (*P. R.*, **17**, 45 (1921))	10.8	10.8
	13.4	15.9
Helium		
Franck and Hertz (*V. d. D. P. G.*, **15**, 34 (1913))	21*	..
Bazzoni (*P. M.*, **32**, 566 (1916))	..	20
Rentschler (*P. R.*, **14**, 503 (1919))	none	27
Franck and Knipping (*P. Z.*, **20**, 481 (1919); *V. d. D. P. G.*, **20**, 181 (1919))	20.5	25.4 (normal atom)
	..	79.5 (double ionization)
Franck and Knipping (*Z. f. P.*, **1**, 320 (1920))	(20.45)	(not present in the purest He)
	21.25	25.3
Horton and Davies (*P. R. S.*, **95**, 408 (1919); *P. M.*, **39**, 592 (1920))	20.5	25.7 (normal atom)
	41	55 (charged atom)
	..	80 (double ionization)
Found (*P. R.*, **16**, 41 (1920))	..	20.5
Stead and Gossling (*P. M.*, **14**, 413 (1920))	..	20.8
Compton (*P. M.*, **40**, 553 (1920))	20.2	25.5
Argon		
Franck and Hertz (*V. d. D. P. G.*, **15**, 34 (1913))	12*	..
Rentschler (*P. R.*, **14**, 503 (1919))	12	17
Horton and Davies (*P. R. S.*, **97**, 1 (1920))	11.5	15.1
Found (*P. R.*, **16**, 41 (1920))	..	15.6
Stead and Gossling (*P. M.*, **40**, 413 (1920))	..	12.5
Neon		
Franck and Hertz (*V. d. D. P. G.*, **15**, 34 (1913))	16*	..
Rentschler (*P. R.*, **14**, 503 (1919))	none	21
Horton and Davies (*P. R. S.*, **98**, 121 (1920))	(11.8	16.7)
	(17.8	20.0)
	(..	22.8)
Nitrogen		
Franck and Hertz (*V. d. D. P. G.*, **15**, 34 (1913))	7.5*	..
Goucher (*P. R.*, **7**, 561 (1916))	7.4*	..
Hughes and Dixon (*P. R.*, **10**, 495 (1917))	7.7*	..

	R. P.	*I. P.*
Bishop (*P. R.*, **9**, 567 (1917))	7.5*	..
Davis and Goucher (*P. R.*, **13**, 1 (1919))	7.5	18
	9.0	..
Karrer (*P. R.*, **13**, 297 (1919))	No. I. P. < 10 volts	
Smyth (*P. R.*, **14**, 409 (1919))	8.29 (strong)	18
	7.3 (doubtful)	..
	6.29 (strong, low pressures)	..
Found (*P. R.*, **16**, 41 (1920))	..	15.8
Mohler and Foote (*J. O. S. A.*, **4**, 49 (1920))	8.18	16.9
Stead and Gossling (*P. M.*, **40**, 413 (1920))	..	17.2

Nitrous Oxide

Bishop (*P. R.*, **9**, 567 (1917))	7.5*	..

Oxygen

Franck and Hertz (*V. d. D. P. G.*, **13**, 34 (1913))	9.0*	..
Hughes and Dixon (*P. R.*, **10**, 495 (1917))	9.2*	..
Bishop (*P. R.*, **10**, 244 (1917))	9.0*	..
Mohler and Foote (*J. O. S. A.*, **4**, 49 (1920))	7.91	15.5

Mercury

Goucher (*P. R.*, **8**, 561 (1916))	4.9*	..
Bishop (*P. R.*, **10**, 244 (1917))	..	10.27
Hughes and Dixon (*P. R.*, **10**, 495 (1917))	..	10.2
Tate (*P. R.*, **10**, 81 (1917))	4.9	10.3
Davis and Goucher (*P.R.*, **10**, 101 (1917))	4.9	10.4
	6.7	..
Hebb (*P. R.*, **11**, 170 (1918))	4.9	4.9
Hebb (*P. R.*, **15**, 130 (1920))	..	3.2
Found (*P. R.*, **15**, 132 (1920))	..	10.1
Kingdom (in print)	..	4.9
Stead and Gossling (*P. R.*, **40**, 413 (1920))	..	10.8
Franck and Einsporn (*Z. f. P.*, **2**, 18 (1920))	(4.68 7.12)	10.38
	(4.9 7.46)	..
	(5.32 7.73)	..
	(5.76 8.35)	
	(6.04 8.64)	
	(6.30 8.86)	
	(6.73)	..

Sodium

Hebb (*P. R.*, **12**, 482 (1918))	1.0	2.5
Wood and Okano (*P. M.*, **34**, 177 (1917))	0.5	..
Tate and Foote (*P. M.*, **36**, 64 (1918))	2.12	5.13

Iodine

Found (*P. R.*, **16**, 41 (1920))	..	8.5
Mohler and Foote (*P. R.*, **15**, 321 (1920))	2.34	10.1

Compton and Smyth (*Science*, 51, 571 (1920)) (*P. R.* 16, 501 (1920))	..	8.0 (atom) 9.4 (molecule) 6.8 (fluorescing molecule)

Carbon Monoxide

Hughes and Dixon (*P. R.*, 10, 495 (1917))	7.2*	..
Found (*P. R.*, 16, 41 (1920))	..	15.0
Stead and Gossling (*P. M.*, 40, 413 (1920))	..	15.0

Hydrochloric Acid Gas

Hughes and Dixon (*P. R.*, 10, 495 (1917))	9.5*	..
Foote and Mohler (*J. A. C. S.*, 49, 1821 (1920))	..	13.7

The following is a table of experimental results obtained for a large number of metallic vapors (and some non-metallic vapors also) by Foote, Mohler, Tate, Stimson, Meggers, and Rognley. They were obtained chiefly by the total and partial current method, and in view of the fact that the experiments were carried out on a systematic and connected plan, it was thought desirable to collect them together.

		R. P.	*I. P.*
Na	Tate and Foote (*P. M.*, 36, 64 (1918))	2.12	5.13
K	Tate and Foote (*P. M.*, 36, 64 (1918))	1.55	4.1
Cd	Tate and Foote (*P. M.*, 36, 64 (1918))	3.88	8.92
Cd	Mohler, Foote and Meggers (*Bur. Stan.*, 1920, 734)	3.95 5.35	9.0
Zn	Tate and Foote (*P. M.*, 36, 64 (1918))	4.1	9.5
Zn	Mohler, Foote and Meggers (*Bur. Stan.*, 1920, 734)	4.18 5.65	9.3
Mg	Foote and Mohler (*P. M.*, 37, 33 (1919))	2.65	7.75
Mg	Mohler, Focte and Meggers (*Bur. Stan.*, 1920, 734)	2.65 4.42	8.0
Hg	Tate (*P. R.*, 10, 81 (1917))	4.9	10.3
Hg	Mohler, Foote and Meggers (*Bur. Stan.*, 1920, 734)	4.76 6.45	10.2
Ca	Mohler, Foote and Stimson (*Bur. Stan.*, 1920, 368)	1.90 2.85	6.01
Tl	Foote and Mohler (*P. M.*, 37, 33 (1919))	1.07	7.3
Pb	Mohler, Foote and Stimson (*Bur. Stan.*, 1920, 368)	1.26	7.93
Rb	Foote, Rognley and Mohler (*P. R.*, 13, 61 (1919))	1.6	4.1
Cs	Foote, Rognley and Mohler (*P. R.*, 13, 61 (1919))	1.48	3.9
As	Foote, Rognley and Mohler (*P. R.*, 13, 61 (1919))	4.7	11.5
N_2	Mohler and Foote (*J. O. S. A.*, 4, 49 (1920); *Bur. Stan.*, 1920, 670)	8.18	16.9
O_2	Mohler and Foote (*J. O. S. A.*, 4, 49 (1920); *Bur. Stan.*, 1920, 670)	7.91	15.5
H_2	Mohler and Foote (*J. O. S. A.*, 4, 49 (1920); *Bur. Stan.*, 1920, 670)	10.4 12.22	13.3 16.5

P	Mohler and Foote (*P. R.*, **15**, 321 (1920); *Bur. Stan.*, 1920, 670)	5.80	13.3
I	Mohler and Foote (*P. R.*, **15**, 321 (1920); *Bur. Stan.*, 1920, 670)	2.34	10.1
S	Mohler and Foote (*P. R.*, **15**, 321 (1920); *Bur. Stan.*, 1920, 670)	4.78	12.2

The following are values obtained by Hughes and Dixon[1] for the first critical potentials for a number of gases. In view of our recent knowledge, it is probable that in most cases they refer to radiating potentials and not to ionizing potentials.

H_2	10.2 volts	CO	7.2 volts
O_2	9.2 volts	CO_2	10.0 volts
N_2	7.7 volts	NO	9.3 volts
Cl	8.2 volts	CH_4	9.5 volts
Hg	10.4 volts	C_2H_6	10.0 volts
HCl	9.5 volts	C_2H_4	9.9 volts
Br	10.0 volts	C_2H_2	9.9 volts

Richardson and Bazzoni[2] carried out an interesting investigation on the extreme ultraviolet radiation emitted by He, H_2 and Hg, when electrons of velocities up to 800 volts were driven through them. The radiation produced was allowed to fall on a metal surface and the velocities of the photo-electrons emitted were measured by a magnetic method. The *fastest* photo-electrons in each case gave the *shortest* wave-length in the radiation. It was found that the shortest wave-length in the radiation was determined by the nature of the gas and was quite independent of the energy of the electrons up to 800 volts (provided, of course, that the minimum energy corresponding to the radiation was present). These results are not directly comparable with those on the radiating potential, for the latter indicate the *first* line in the series, while these experiments indicate the shortest line of appreciable intensity in the series. The results are as follows:

	Shortest wave-length	Corresponding voltage
H_2	$> \lambda 830 \quad < \lambda 950$	$<14.8 \quad >13.0$
He	$> \lambda 420 \quad < \lambda 470$	$<29.4 \quad >25.7$
Hg	$> \lambda 1000 \quad < \lambda 1200$	$<12.4 \quad >10.2$

It will be seen that a large amount of evidence as to the ionizing and radiating potentials has been amassed. It seems certain that each gas or vapor has at least one radiating potential and one ionizing potential, both clearly marked. Cases in which ionization occurs at the radiating potentials are ignored as they will be considered later as examples of "cumulative effects." It remains to be seen how these results can be accounted for theoretically. The most reliable values for the critical potentials can be associated with certain important features in the spectra of the gases in the majority of cases. For hydrogen and helium, Bohr's theory is found to link up most of the results satisfactorily, while in the case of the metals for which series are known in some detail, consistent relations can be found.

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[1] *P. R.*, **10**, 495 (1917).

[2] *P. M.*, **34**, 285 (1917).

BOHR'S THEORY FOR HYDROGEN AND HELIUM

Hydrogen. According to Bohr, the negative energy of the hydrogen atom pictured as a simple system of one positive nucleus with one electron rotating around it in a circular orbit, is

$$W = \frac{2\pi^2 e^4 m}{h^2} \frac{1}{\tau^2} = W_0 \frac{1}{\tau^2}$$

where W_0 is the negative energy of the innermost possible orbit (for which $\tau = 1$) and τ is an integer. (Only those orbits for which τ is an integer are possible, on Bohr's theory.) The innermost possible orbit ($\tau = 1$) corresponds to the normal hydrogen atom. Whenever the atom undergoes a change in configuration, such that the atom passes from orbit τ_2 to τ_1 ($\tau_2 > \tau_1$) an amount of energy is liberated amounting to

$$W_0 \left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right]$$

An essential feature of Bohr's theory is that this liberation of energy determines the frequency of the monochromatic light emitted during the change, through the quantum relation

$$h\nu = W_0 \left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right]$$

or

$$\nu = \frac{W_0}{h}\left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right] = K\left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right]$$

where K is known as Rydberg's number which equals 3.290×10^{15}.

To each pair of integral values for τ_1 and τ_2 corresponds a line, and these lines fall into series, each series having different values for τ_1 and each member in a series having a different value for τ_2. Spectroscopic identification of the various series has led to a determination of K′, in the corresponding "wave number" equation

$$\frac{1}{\lambda} = K'\left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right]$$

as 109678.3 correct to about one part in a million.[1] Our K (Rydberg's constant) is related to K′ through the velocity of light ($K = cK'$) and is therefore known to the same degree of accuracy as the velocity of light is known. Its value is 3.290×10^{15} as far as the first four significant figures.

We shall now proceed to calculate the potential corresponding to the limit (λ_0) of the shortest wave-length series in hydrogen ($\tau_1 = 1$, $\tau_2 = \infty$). This frequency ν_0 is important, in that through the quantum relation we have at once the energy required to remove the electron from the innermost orbit (*i. e.*, from a normal hydrogen atom) to infinity, in other words, the energy necessary to ionize the hydrogen atom.

$$V_0 e = h\nu_0 = W_0 = Kh$$

Hence

$$\begin{aligned} V_0 &= K\frac{h}{e} \\ &= 3.290 \times 10^{15} \times \frac{6.547 \times 10^{-27} \times 299.86}{4.774 \times 10^{-10}} \text{ volts} \\ &= 13.52_4 \text{ volts.} \end{aligned}$$

The corresponding λ_0 is 911.74 Ångstrom units (which may also be identified directly as the reciprocal of Curtis's value for the hydrogen spectrum constant).

According to Bohr, the negative energies of the hydrogen atom, the hydrogen molecule (*i. e.*, two separated positive nuclei with two electrons rotating symmetrically around the line joining them as axis) and the charged hydrogen molecule (*i. e.*, the hydrogen molecule just referred to with one electron removed) are as follows:

Neutral hydrogen atom	W_0
Neutral hydrogen molecule	2.20 W_0
Charged hydrogen molecule	0.88 W_0

The following energies are required to effect the changes indicated:

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[1] Curtis, *P. R. S.*, **96**, 147 (1919).

			Corresponding volts
Neutral atom ⟶ Charged atom....	$W_0 - 0$	$= W_0$	(13.52)
Neutral molecule ⟶ charged molecule.... **(Bohr considers this less likely to represent ionization of the molecule than the following)**	$2.20\ W_0 - 0.88\ W_0$	$= 1.32\ W_0$	(17.85)
Neutral molecule ⟶ Neutral atom and charged atom....	$2.20\ W_0 - W_0$	$= 1.20\ W_0$	(16.22)
Neutral molecule ⟶ Two neutral atoms (dissociation)....	$2.20\ W_0 - 2\ W_0$	$= 0.20\ W_0$	(2.70)
Neutral atom ⟶ Neutral atom.... **(Electron shifts orbit 1 ⟶ orbit 2 giving first radiating potential)**	$W_0 \left[\frac{1}{1^2} - \frac{1}{2^2}\right]$	$= 0.75\ W_0$	(10.14)

Of the experimental results which distinguish between radiating and ionizing potentials, those by Mohler and Foote, and by Horton and Davies, are put forward as being in fair accord with the predictions of Bohr's theory. It is by no means clear, however, why experimental investigations on ordinary diatomic hydrogen should give the critical potentials predicted for *atomic* hydrogen. Although it is known that an incandescent filament dissociates molecular hydrogen, and that atomic hydrogen is present with intense electron currents, the amount of atomic hydrogen in most experiments will be, at the most, but a small fraction of the undissociated hydrogen. Hence it is not clear why critical values associated with simple collisions between atomic hydrogen and electrons should be found.

An exceedingly suggestive point of view has been put forward by Franck, Knipping and Krüger in support of their experimental results. According to them, the first critical potential at 11.5 volts is an *ionizing* potential and not a radiating potential, and it is maintained that this corresponds to the detachment of an electron from a hydrogen molecule. That a positively charged hydrogen molecule can exist is shown clearly by Sir J. J. Thomson's work on positive rays[1] from which he deduced the ionizing potential of the hydrogen molecule to be 11 volts, a valuable result in that the method is entirely different from the methods here considered. (From energy considerations, Bohr considers that the formation of the positively charged hydrogen molecule is less likely to happen than the breaking up of the molecule into a neutral atom and a charged atom. This gives 16.22 volts instead of 17.85 volts (see table above). This means that, on Bohr's theory, no positively charged hydrogen molecule could exist.) Franck, Knipping and

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[1] "Rays of Positive Electricity," p. 36, Longmans.

Krüger explain the radiating potential which they obtained at 13.6 volts as the simultaneous dissociation of the molecule into atoms and the displacement of the electron in one of them to the second Bohr orbit, so that it is in a position to give out radiation of frequency K $[1/1^2 - 1/2^2]$ corresponding to 10.14 volts. They consider 3.5 volts to represent the best experimental value of the work of dissociating a hydrogen molecule. (Langmuir's value is 3.6 volts.) Thus the radiating potential at 13.6 volts is taken to correspond to dissociation plus radiation from an atom (theoretically = 3.5 + 10.14 = 13.6 volts). Similarly the ionizing potential at 17.1 volts is accounted for by dissociation plus ionization of an atom (theoretically = 3.5 + 13.52 = 17.0 volts). Again the ionizing potential at 30.4 volts is accounted for by dissociation plus ionization of both atoms (theoretically = 3.5 + 2 × 13.52 = 30.5 volts). (On the same lines we might expect a radiating potential at 3.5 + 2 × 10.14 = 23.8 volts, but none is recorded.) In support of these results, Compton and Olmstead[1] find ionizing potentials at 10.8 volts and at 15.9 volts, and a radiating potential at 13.4 volts. They find, however, radiation at 10.8 volts, contrary to Franck, Knipping and Krüger. The proportion of radiation to ionization between 10.8 and 15.9 volts depends largely on conditions such as gas pressure and electron current. It may be that cumulative effects occur and that in some cases atomic hydrogen is present in sufficient amount to show its own critical potentials. It will be noticed that the earlier results of Davis and Goucher tend to support the view of Franck, Knipping and Krüger rather than the other. The distinction between the two views as to the interpretation of the experimental results is of fundamental importance in the theory of the hydrogen molecule. Even if we restrict ourselves to the results published during the last two years, it will be seen that there is lack of agreement as to the critical potentials of hydrogen, and still more, as to their interpretation.

While Bohr's theory gives a wonderfully accurate picture of the hydrogen atom, it gives an inexact picture of the hydrogen molecule. The calculated work of dissociation corresponds to 2.70 volts, while Langmuir's experimental work yields 3.6 volts. On Bohr's theory, an impact between an electron and a hydrogen molecule will result in the formation of a neutral atom and a charged atom, and not in the formation of a positively charged molecule, but the evidence discussed in the last paragraph shows that it is produced. Langmuir[1] has suggested a new model for the hydrogen molecule. Each electron keeps to its own path, the paths being arcs of curves situated in a plane perpendicular to the line joining the two nuclei. The electron in the path *ab* always keeps the same distance from *a*, as the other electron does from *a'*, fig 22. Langmuir makes use of the known work of dissociation to calculate the magnitude of the orbits and the negative energy of the system. For the positively charged molecule, he assumes that the single electron oscillates along a straight line perpendicular to the line joining the nuclei, fig. 23. Two ways of applying the quantum theory are suggested to determine the dimensions of the system. On taking the difference between the energies of the neutral molecule and of the charged molecule, Langmuir obtained 10.15 and 14.10 volts as the ionizing potential, according as to which of the two ways he deduced the energy of the charged molecule. The model at least offers a possible explanation of the stable charged molecule and of an ionizing potential near to 11 volts.

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[1] *P. R.*, **17**, 45 (1921).

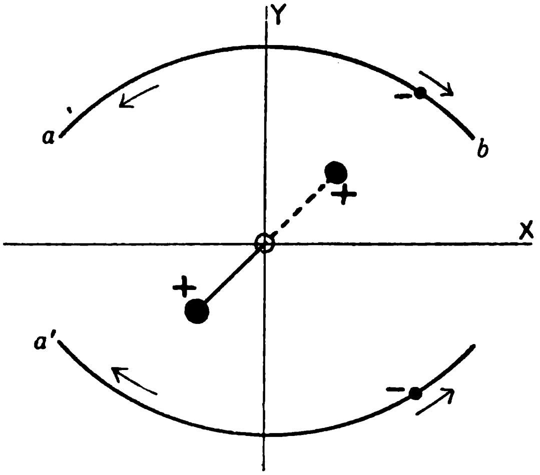

Fig. 22

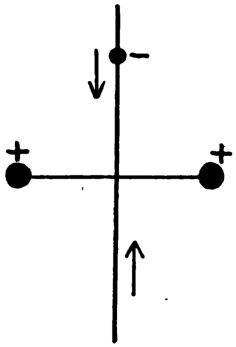

Fig 23.

Helium. According to Bohr, the negative energy of the helium atom, pictured as a system of two electrons rotating around a doubly charged nucleus, is

$$W = 6.13\ W_0$$

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[1] *Science*, 52, 433 (1920).

The negative energy of the *positively charged* helium atom, *i. e.*, with only one electron rotating around the same nucleus is

$$W = 4.00\ W_0.$$

This positively charged atom is very similar to the hydrogen atom, except for the charge on the nucleus, and should give out series of lines represented by

$$\nu = \frac{4\ W_0}{h}\left[\frac{1}{\tau_1^2} - \frac{1}{\tau_2^2}\right].$$

Several lines (called "enhanced" lines) belonging to these series have been identified by Evans, Paschen and Fowler in the spectrum of the disruptive discharge through helium, where we may suppose that the flow of current is so intense, momentarily, that many helium atoms ionized by one impact are again struck before they return to the normal state. Compton and Lilly[1] have obtained the enhanced line λ 4868 in an intense helium arc.

The following energies are required to effect the changes indicated:

			volts
A.	Neutral atom ⟶ positively charged atom................	$6.13\ W_0 - 4.00\,W = 2.13\ W_0$	(28.81)
B.	Neutral atom ⟶ doubly charged atom................	$6.13\ W_0 - 0 = 6.13\ W_0$	(82.90)
C.	Charged atom ⟶ doubly charged atom................	$4.00\ W_0 - 0 = 4.00\ W_0$	(54.10)
D.	Pos. atom ⟶ pos. atom....... (State 1) (State 2) (Giving first R. P. of charged atom)	$4.00\ W_0\left[\frac{1}{1^2} - \frac{1}{2^2}\right] = 3.00\ W_0$	(40.57)

No theoretical value for the radiating potential of the neutral helium atom has been given. It will be seen that the experimental ionizing potentials for the helium atom are around 25.5 volts, which differs from the theoretical value (28.86 volts) by more than errors of observation.

The agreement between the experimental results for helium seems to be better than in the case of other gases. Excepting the values of 20 volts for ionization, which can easily be explained as "cumulative" effects, as will be seen later, it appears to be well established that the ionizing potential for the normal atom is close to 25.5 volts and the radiating potential to 20.4 volts. The former value is definitely lower than Bohr's theoretical values which yield 28.81 volts, by about 3.3 volts. Both Horton and Davies, and Franck and Knipping found that a second type of ionization occurred at about 79.7 volts, again about 3.3 volts lower than Bohr's theoretical value 82.90 volts, corresponding to the simultaneous removal of *both* electrons. If, however, we calculate the ionizing potential for a *charged* helium atom, *i. e.*, the helium nucleus with *one* electron, by subtracting the first ionizing potential from the second, we get according to Horton and Davies 80.0 — 25.7 = 54.3 volts, and according to Franck and Knipping, 79.5 — 25.4 = 54.1 volts. These values are exceedingly close to the theoretical value for the *charged* helium atom, viz., 54.10 volts. We find here, therefore, a close parallel to the case of hydrogen. Bohr's theory is quantitatively exact when we have to deal with a nucleus and *one* electron, whether that nucleus is singly or doubly charged as in the case of the hydrogen atom and the (charged) helium atom, respectively. Bohr's model is not quantitatively exact when there are two electrons outside the nucleus to be considered as in the case of the hydrogen molecule and the normal helium atom. By a skilful variation in the choice of the pressure and the electron current, Horton and Davies were able to show in the same apparatus the radiating and ionizing potentials of the normal helium atom, the ionizing potential corresponding to the removal of both electrons from the normal atom, and the radiating and ionizing potentials for the charged helium atom. The latter were obtained by using a very intense stream of electrons so that there was opportunity for electrons to hit helium atoms already ionized.

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[1] *A. P. J.*, **52**, 1 (1920).

Franck and Knipping[1] discovered the existence of a second radiating potential for helium by means of an ingenious application of the Schuster-Rydberg principle. According to this principle, the difference between the frequency of the first line of a series and the frequency of the limit of the same series is also the frequency of the limit of another series. Now these frequencies can be replaced by their corresponding critical potentials. The radiating potential, 20.5 volts, corresponds to the first line (1X — 1Y) of a series, and the ionizing potential, 25.4 volts, corresponds to the limit (1X) of the same series. (This notation will be explained in a later section.) Hence the *difference* of these values should correspond to the *limit* of *another* series.

$$
\begin{aligned}
& 1X - 1Y = 20.5 \text{ volts} \\
& 1X \quad\quad\;\; = 25.4 \text{ volts} \\
\text{Hence} \quad & \quad\quad 1Y = \;\; 4.9 \text{ volts}
\end{aligned}
$$

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[1] *P. Z.*, **20**, 487 (1919).

The frequency of the limit (1Y) of this other series, corresponding to 4.9 volts, should be λ 2520. Franck and Knipping recognized that this was close to the limits of the two principal series for helium λ 2600 (4.74 volts) and λ 3122 (3.95 volts), respectively. (These series are sometimes referred to as the helium and parhelium series.) The natural assumption was then made that the limit 1Y of the hypothetical series was identical with the known limit, 1*s* (λ 2600), of the principal series, 1*s*-*mp*, for helium. The existence of the limit, 1S (λ 3122), of the parhelium series suggested that there should be another radiating potential. The two radiating potentials should therefore be

$$25.4 - 4.74 = 20.66 \text{ volts}$$
$$25.4 - 3.95 = 21.45 \text{ volts}$$

i. e., there should be two radiating potentials, separated by .8 volt. Careful observations on pure helium showed this to be the case.

In a second paper on helium, Franck and Knipping[1] make further important contributions to our knowledge of the radiating potentials of helium. They start with the view that in the normal helium atom the two electrons cannot exist in co-planar orbits but that they are to be found in crossed orbits, *i. e.*, the planes of the orbits are inclined to each other at right angles. (Landé has discussed such orbits from a theoretical standpoint.) Thus the only possible 1-quantum state for the helium atom is that in which the orbits are at right angles (crossed orbits). The next state, the 2-quantum state, can exist in two forms, *i. e.*, with crossed orbits and with co-planar orbits. Now the transition from the 1-quantum state to the 2-quantum state requires different amounts of energy according as to whether the second state is that of crossed orbits, or that of co-planar orbits. According to Landé, the two possible forms of the second state (crossed and co-planar orbits) for the atom are taken to account for the two principal series (helium and parhelium). Lines of helium principal series (and other series having the same limit) are given out when an electron falls back to give the 2-quantum, co-planar state, and lines of the parhelium principal series (and other series having the same limit) are given out on return to the 2-quantum crossed state. The two radiating potentials, previously found, and differing by .8 volt, correspond to displacements of an electron from the 1-quantum state to the 2-quantum crossed state and to the 2-quantum co-planar state, respectively. Fig. 24 represents diagrammatically the two radiating potentials and the origin of the helium and parhelium series.

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[1] *Z. f. P.*, **1**, 320 (1920).

Franck and Knipping investigated the radiating potentials by measuring the photo-electric effect of the radiation, much as in the Lenard method. The electrons were accelerated through a gauze, then were allowed to collide with molecules in a comparatively large volume bounded by a second gauze, beyond which was the photo-electric plate. The most important result of this paper is that in the very purest helium, no trace of the 20.45 volt radiating potential could be obtained. In such a case, the 21.25 volt effect shows up alone. However, the slightest amount of impurity (such as can be obtained by warming up the charcoal on slightly lowering the liquid air for a short time) causes the 20.45 volt to appear again. The amount of impurity was considered too small to show any ionization or radiation by itself. It is suggested by the authors that the 2-quantum co-planar state is a stable state, and that the helium atom will not spontaneously return from it to the normal 1-quantum state. Thus they account for the non-appearance of radiation in the purest helium at 20.45 volts. (It is to be presumed that they showed that, although there was an absence of *radiation*, there were *inelastic* collisions at this accelerating voltage in the *purest* helium.) The 2-quantum co-planar helium atom resembles the hydrogen atom to some extent, and may possibly be capable of entering into transient combination with atoms having electron affinities, such as oxygen. The appearance of the 20.45 volt radiating potential is explained on the

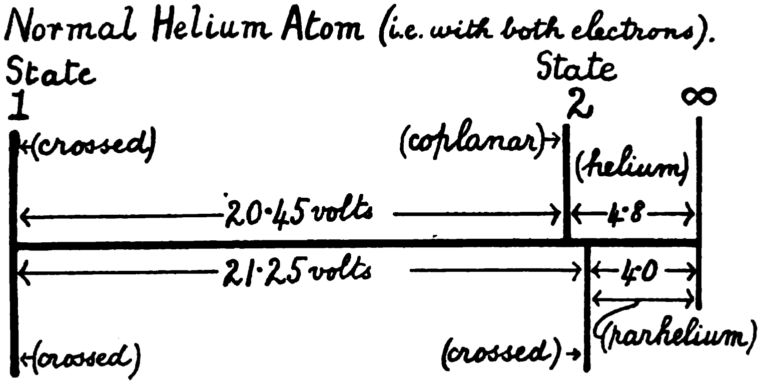

FIG. 24.

assumption that the short-lived compounds formed with 2-quantum co-planar helium atoms break up with the emission of radiation corresponding to 20.45 volts. The impurities thus have a sort of catalytic effect in promoting the return of the 2-quantum co-planar helium atom to the normal 1-quantum state.

The idea of electrons displaced to certain orbits outside the normal 1-quantum orbit being unable to return, and so giving rise to a "metastable" state has been suggested by several facts in spectroscopy. Thus the resonance line of mercury λ 2536, 1S — $1p_2$, is called out strongly by collisions of mercury atoms with electrons having energy above 4.9 volts, while the other lines of the triplet of which λ 2536 is the middle member, are so feeble that they have not been detected until recently. It would appear that the falling back from the $1p_1$ and the $1p_3$ orbit in mercury to the normal 1S orbit does not occur nearly so easily as from the $1p_2$ orbit.

The conception of helium atoms in a metastable state makes the explanation of ionization below the ionizing potential by the action of the cumulative effects of successive collisions much more plausible than before (see later section on cumulative effects, particularly the part dealing with Compton's work on helium). The absence of radiation when pure helium is bombarded by 20.45 volt electrons and presumably being changed continuously into the metastable state, opens up interesting possibilities as to the physical and chemical properties of this new type of helium.

Franck and Knipping found several discontinuities in their curves showing the photo-electric effect of radiation, between the first radiating potential and the ionizing potential. They attributed these to emission lines in the spectrum of helium. The values of all the radiating potentials found are given in the following table. The first value (20.45 volts) is enclosed in brackets to show that it does not appear in the purest helium.

Observed	λ from $h\nu = Ve$	Calculated
(20.45)	(610)	(20.45)
21.25	585	21.25
21.9	569	21.85
23.6	523	23.7
...	..	...
...	..	...
25.3	493	25.23

A series formula of the form

$$\nu = \frac{N}{(1 + x)^2} - \frac{N}{(m + y)^2}$$

was used to calculate the values in the last column. The constants were determined from the experimental values of two of the potentials, and the remaining potentials calculated. It will be seen that the results are in good agreement with the formula.

Professor Lyman in a letter to the writer states that he has found, spectroscopically, a strong line in helium at λ 585. This value corresponds to the *second* radiating potential, 21.25 volts. No line appeared to correspond to the commonly found radiating potential at 20.45 volts. It is unlikely that Lyman's helium (in a vacuum spectroscope) could be so free from impurities as that for which Franck and Knipping found the 20.45 volt effect to vanish. Radiation corresponding to this at about λ 605 might well have been expected.

Other Gases. As we have no satisfactory atomic models of the molecules of other gases, we are compelled to look in another—perhaps less fundamental—direction and see if we can establish some correlations. On the analogy of satisfactory correlations in the case of metallic vapors, attempts have been made to apply the same results to gases. Unfortunately our knowledge of the spectrum in the extreme ultraviolet, and especially of series there, is not nearly so complete as in the region λ 7000–λ 2000. Smyth and Mohler and Foote identified their values (8.29 and 8.18, respectively) with the nitrogen doublet λ 1492.8 and λ 1494.8, which would correspond to 8.26 volts. According to Lyman, oxygen has an absorption band in the ultraviolet, with its center about λ 1400. This expressed in volts is 8.8 volts, and possibly corresponds to the experimental critical potentials about 9.0 volts. No other correlation, outside metallic vapors, appears to have been made. Further work on the emission and absorption spectra of gases and vapors in the extreme ultraviolet is much to be desired to supply data for comparison with critical potentials.

In this section we may refer to Compton and Smyth's work[1] on iodine. They found *two* ionizing potentials, in iodine vapor, one corresponding to the molecule (10.0 volts) and the other to the atom (8.5 volts). As the temperature is raised, and the amount of dissociation increased, the intensity of the 8.5 volt effect increases with respect to the 10.0 volt effect, as would be expected. The difference corresponds to the value of the work necessary to dissociate iodine as determined by the methods of physical chemistry.

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[1] *Science*, **51**, 571 (1920); *P. R.*, **16**, 501 (1920).

SPECTRAL SERIES NOTATION*

The spectra of many metals, particularly those of the alkali metals and of the alkaline earths, can be resolved into a number of series. The frequencies of lines in a series of lines in the spectrum of an element may be represented as the difference of two terms, such as

$$\nu = \frac{N}{(1 + f(S))^2} - \frac{N}{(m + f(P))^2}$$

which represents the Principal Series. To a first approximation, the functions are such that the difference may be written

$$\nu = \frac{N}{(1 + S)^2} - \frac{N}{(m + P)^2}$$

"N" is a universal constant. "S" and "P" are constants for this particular series, and *m* takes successive integral values up to infinity, each value corresponding to a line in the series. It will be seen that as *m* increases indefinitely, the frequencies become closer and closer together, and when $m = \infty$, we have only the first term left which is called the "convergence frequency" or "limit" of the series. The first line of the series is usually that for which *m* is the smallest integer which will make the expression positive. For example, the first line of the Principal Series is

$$\nu = \frac{N}{(1 + S)^2} - \frac{N}{(1 + P)^2}$$

A short notation for this series is

$$\nu = 1S - mP$$

The chief series are as follows:

Principal	$1S - mP$	$m = 1, 2, 3, 4$..............
Sharp	$1P - mS$	$m = 2, 3, 4, 5$..............
Diffuse	$1P - mD$	$m = 2, 3, 4, 5$..............
Fundamental	$2D - mF$	$m = 2, 3, 4, 5$..............

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* The author wishes to thank Professors A. Fowler and F. A. Saunders for valuable information in this connection. The author has adopted their notation, which is that generally used by American and English spectroscopists, in preference to that often followed by writers on ionizing and radiating potentials, as it seems desirable for the sake of uniformity that all should follow the same notation. The notation will be used by Professor Fowler in his forthcoming book "Report on Series Spectra" to be published by the London Physical Society. Much information on series notation will be found in papers by Professor Saunders (*A. P. J.*, **41**, 323 (1915); **50**, 151 (1919); **51**, 23 (1920)).

"Combination" series are also found, formed by taking terms from two different series of those mentioned above; *e. g.*, 1S — mD is a combination series.

The radiating and ionizing potentials of the alkali metals are found to be related to the "principal series of doublets," for which the above notation is used, except that Greek letters are used instead of capitals. When it is necessary to distinguish between the two lines of a doublet, suffixes are used. Thus the two lines forming the familiar doublet of sodium λ 5890 and λ 5896 are $1\sigma - 1\pi_1$, and $1\sigma - 1\pi_2$, respectively.

When we deal with the radiating and ionizing potentials of the metals of the second column in the periodic table, we have to do with the "principal series of single lines" or "singlets," as they are frequently called, 1S — mP, and also with a combination series formed by subtracting from the convergence frequency of the principal series of singlets 1S, the terms mp_2 of the principal series of triplets (middle terms only). The combination series referred to is 1S — mp_2. Thus the first line of the principal series of singlets 1S — mP ($m = 1$) for mercury is λ 1849, the first line of the combination series 1S — mp_2 ($m = 1$) is λ 2537, while the limit for both series, 1S, is at λ 1188.

A method of visualizing the origin of series in the Hg spectrum is shown in fig. 25. The various vertical lines 1S, 1P, 2S, etc., and $1p_1$, $1p_2$, $1p_3$, etc., represent some of the possible stationary states of the atom, in Bohr's sense. We have no means of knowing the actual spacing between the orbits, or how they are arranged in such a complex system as the Hg atom, but we do know the wave-length of the lines given out as an electron falls back from one of the outer stationary orbits to one of the inner orbits. Since the emission of lines is supposed to be governed by the quantum relation $Ve = h\nu$, we know the energy emitted by the atom for each line, and hence the diagram is plotted in terms of energy (expressed in volts) below and in the equivalent wave numbers ($= 1/\lambda = \nu/3(10)^{10}$) above. The diagram therefore shows the energy of the atomic system according to which of the stationary orbits is occupied by the outermost electron, and the wave number of the line emitted as the electron falls from an outer orbit to an inner orbit. (Possibly it would be more correct to say that the vertical lines specify the energy of the various possible configurations of the atom, and that it is conjectured that these configurations correspond to the atom with its outermost electron in one or other of the possible stationary orbits. The energy relations are definite, the way in which they are accounted for is still to be settled.) Thus the energy given out by the atom when the line λ 2536 is emitted is measured by 4.9 volts, and the energy given out when the electron is completely removed is 10.4 volts. In the normal unexcited atom, the orbits outside the 1S orbit are supposed to be unoccupied. Evidence for this will be given later. In the upper part of the diagram will be found a few of the spectral lines (shown by horizontal lines) in three singlet series, viz., the Principal, 1S−*m*P, the Sharp 1P−*m*S, and the Diffuse 1P−*m*D. In the lower part, one series of triplets, 1*p*−*ms*, is illustrated. In the middle, several lines belonging to combination series are shown, *e. g.*, 1S−*mp*. Fig. 25 is shown to illustrate Franck and Einspörn's paper which will be considered later. The full horizontal lines are those which they identified through radiating potentials. For the present discussion, the distinction between full and dotted horizontal lines is to be ignored.

The following table shows the correspondence between the notation used by Ritz and Paschen and that used here, following Fowler and Saunders.

Ritz and Paschen	Fowler and Saunders
1.5S, 2.5S, 3.5S	1S, 2S, 3S
2P, 3P	1P, 2P
3D, 4D	2D, 3D
1.5S — mP, $m = 2,3$	1S — mP, $m = 1,2$
2P — mS, $m = 2.5, 3.5$.	1P — mS, $m = 2,3$
2P — mD, $m = 3,4$	1P — mD, $m = 2,3$
1.5S — mp_2, $m = 2,3$	1S — mp_2, $m = 1,2$

Metallic Vapors. It was noticed by Davis and Goucher that in the case of mercury vapor there were radiating potentials corresponding to the lines λ 2536 and λ 1849 and an ionizing potential corresponding to λ 1188, the limit of both the series to which λ 2536 and λ 1849 belong. This gave the clue to another method of determining the ionizing potentials and was used very successfully by McLennan and Young.[1] It was assumed that any method which would give the convergence frequency of the principal series would at the same time give the ionizing potential through the quantum relation. McLennan and Young made use of the property that lines in the principal series are strongly marked absorption lines when light is passed through the vapor of the element. In this way they were able to pick out the lines in the principal series of a number of elements, and so to calculate the convergence frequency and the ionizing potential. They gave the following values of the ionizing potentials calculated by this method:

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[1] *P. R. S.*, 95, 273 (1918).

Hg	10.45 volts	Sn	5.70 volts
Zn	9.4 volts	Ba	5.21 volts
Cd	9.0 volts	Na	5.13 volts
Mg	7.65 volts	Ka	4.32 volts
Ca	6.12 volts		

Mohler and Foote, and others, have made extensive determinations of radiating and ionizing potentials of a large number of metals. They conclude that in the case of the elements Na, K, Rb and Cs (Group I of the Periodic Table) the ionizing potential corresponds to 1σ and the radiating potential to the shorter line $1\sigma - 1\pi_2$ of the doublet, $1\sigma - 1\pi$, in the principal series of doublets. For the elements Mg and Ca, Hg, Zn, Cd, they found that the radiating potential corresponds to the first line of the combination series $1S - 1p_2$ and the ionizing potential to 1S. There is, however, in Ca a radiating potential at $1S - 1P$ as well, and possibly a corresponding one would be found for Mg. Davis and Goucher have shown that a second radiating potential exists for Hg corresponding to $1S - 1P$. It seems safe to generalize that 1S corresponds to the ionizing potentials of the elements in this group, and that $1S - 1p_2$ and $1S - 1P$ correspond to radiating potentials, although the latter may often be masked by the former.*

Not enough is known about series in the spectra of elements outside the first two groups. Mohler and Foote have indeed suggested that the experimental values of the ionizing and radiating potentials for such elements may be used as starting points in the search for series relations.

SINGLE AND MULTIPLE LINE SPECTRA

The work of Franck and Hertz[1] in 1914 must be regarded as the starting point of all work on radiating potentials, for they were the first to demonstrate that by bombarding the atoms of mercury vapor with electrons, the single line λ 2536 appeared as soon as the energy of the electrons exceeded 4.9 volts. This was the first proof of the quantum relation as applied to the direct production of radiation by electron impacts, and, moreover, served to identify the radiation associated with the radiating potential as monochromatic light whose wave-length is that of the first line in an important series of the spectrum. McLennan and Henderson[1] and McLennan[2] extended this investigation to other metals. It was found that for Hg, Zn, Cd and Mg, electrons must possess a certain characteristic minimum velocity before the single lined spectrum of these elements could be called out, and that this minimum velocity agreed well with the value deduced by the quantum relation from the corresponding wave-lengths. These wave-lengths λ 2536 for Hg, λ 3076 for Zn, λ 3260 for Cd, and λ 2852 for Mg are all first lines of important series. The first three lines belong to the combination series, being $1S - 1p_2$, while the Mg line is the $1S - 1P$ line. It should be noted here that Mohler and Foote in their experiments on radiating potentials found that the frequency $1S - 1p_2$ could be excited with Mg just as with the other elements. They state that their method really measures the points of inelastic impact hitherto taken to indicate the wave-length of the principal radiation. For Mg and Ca (and presumably Ba and Sr) the inelastic collision method emphasizes the frequencies $1S - 1p_2$ and indicates the presence of $1S - 1P$ while the spectroscopic evidence emphasizes $1S - 1P$.

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* In a recent paper, Foote, Mohler and Meggers (Bur. Stan., 1920, 725) find that every element in Group II, which they tried, viz., Zn, Cd, Hg, Mg and Ca, has two radiating potentials, corresponding to $IS - 1p_2$ and $IS - IP$.

[1] *V. d. D. P. G.*, 16, 512 (1914).

McLennan and Henderson found that as the speed of the electron was increased nothing but the single line was obtained until the speed corresponding to the head of the series was reached, at which point *all* the lines of the series appeared together. It would seem natural to expect that shorter lines than the single lines would appear when electrons of the proper velocity were driven through the vapor. McLennan and Ireton[3] investigated this carefully and found that in the case of Zn and Cd *two* lines, and only two lines, could be called out by electrons having just sufficient energy to call out the shorter. (If the conditions are not such as to render cumulative effects negligible, other lines may appear as well.) The first line called out in each case is the first line of the combination series 1S — $1p_2$ and the second line is the first line of the principal series 1S — 1P.

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[1] *P. R. S.*, **91**, 485 (1915).

[2] *Ibid.*, **92**, 305 (1916).

[3] *P. M.*, **36**, 46 (1918).

Foote and Meggers[1] have made some very interesting investigations on the spectrum of Cs excited by slow electrons. Measurements of the energy in the various spectral lines were made for different values of the accelerating potential. It was concluded that the two lines of the doublet 1σ — 1π were called out simultaneously, and that they were called out only when the electrons had energy in excess of that corresponding to the *shorter* of the two lines forming the doublet. No other lines were called out until the ionizing potential was reached. This result seems to be in conflict with that of Franck and Knipping on helium, and with that of Franck and Einspörn on mercury. There seems to be no *a priori* reason for supposing that the lines of higher frequencies in either the 1S–1P or the 1S$-1p$ series cannot be excited, with electrons of appropriate energy, if the first lines can be excited. One would expect the mechanism to be the same for all lines of the series, the only difference being the amount of energy involved. Possibly the intensities of the lines of higher frequencies are too feeble, under most experimental conditions, to allow them to be detected.

Franck and Einspörn[2] have recently made a very important contribution to our knowledge of the radiating potentials of mercury. They measured the photo-electric effect produced by electron impacts with mercury atoms, as a function of the potential accelerating the electrons. By taking great care to use pure mercury vapor, to secure absolutely steady electron emission from the source and to increase the accelerating potential by very small steps, they found no less than eighteen discontinuities in their curves between the first radiating potential and the ionizing potential. (They used a modified Lenard method.) The results are given in the table. They were able to identify a number of the discontinuities with known lines. In some cases, e. g., No. 17 and 17′, the theoretical values corresponding to possible interpretations of the breaks in the curves are so close that it is not possible to decide which interpretation is correct. Corresponding to No. 3 there is the known optically absorbing region from λ 2313 to λ 2338, which does not fit into any known series relations. There are some breaks, *e. g.*, 6, 7, 9, ... which do not correspond to any spectrum lines known at present. The break, No. 5, is of interest in that Franck and Einspörn suggest that it is due to the complete expulsion of an electron from the orbit $1p_3$, *i. e.*, to *ionization* of an abnormal Hg atom, abnormal in the sense that in the normal Hg atom, no electrons exist outside the orbit 1S. It is well known that in the triplet 1S — $1p$ the middle term 1S — $1p_2$ is far more intense than either 1S — $1p_1$ or 1S — $1p_3$. The electrons apparently have much more difficulty in dropping back from orbits $1p_1$ or $1p_3$ to 1S than from $1p_2$ to 1S, consequently it has been suggested that a mercury atom with electrons in these orbits is in a semi-stable state. Hence there is a

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[1] *P. M.*, **40**, 80 (1920).

[2] *Z. f. P.*, **2**, 18 (1920).

No.	Observed V.	Strength *s*=strong, *m*=medium, *w*=weak	λ	Series	Calculated V.
1	4.68	*w*	2656.5	1S — $1p_3$	4.66
2	4.9	very *s*, especially at high pressures	2537	1S — $1p_2$	4.86
3	5.32	*w*	2338 2331		5.28 5.34
4	5.47	*w* at mean pressures *s*	2270.6	1S — $1p_1$	5.43
5	5.76	*s*	2150	$1p_3$	5.73
6	6.04	*w*	2043		...
7	6.30	*w*	(1956)		...
8	6.73	*m*	1849-6	1S — 1P	6.67
9	7.12	*s* high pressures *w* low pressures	(1733)		...
10	7.46	*m*	1656		...
11	7.72	*m*	1603.9	1S — 1*s*	7.69
12	8.35	*w*	(1447)		...
13	8.64	*s*	1435.6	1S — $2p_2$	8.58
14	8.86	*m*	1402.7	1S — 2P	8.79
14′		*m*	1400	1S — 2*d*	8.81
15	9.37	*w*	2656.5 2656.5		2 × 4.66 = 9.32
16		*w*	1307.8	1S — $3p_2$	9.44
16′	9.60	*w*	2656.5 2537		4.66 + 4.86 = 9.52
17	9.7	*m*	2537 2537		2 × 4.86 = 9.72
17′		*m*	2537 1268.9	1S — 3P	9.73
18	10.38	*s* low pressures *w* high pressures	1187.9	1S	10.39

far greater probability of impinging electrons hitting an atom in these states, and so causing ionization or radiation, of another type, than for the case of an atom with an electron in the orbit $1p_2$. The diagram (based on those given in Franck and Einspörn's paper) shows some of the possible orbits (in Bohr's sense) in the mercury atom (fig. 25). They are so spaced as to measure the

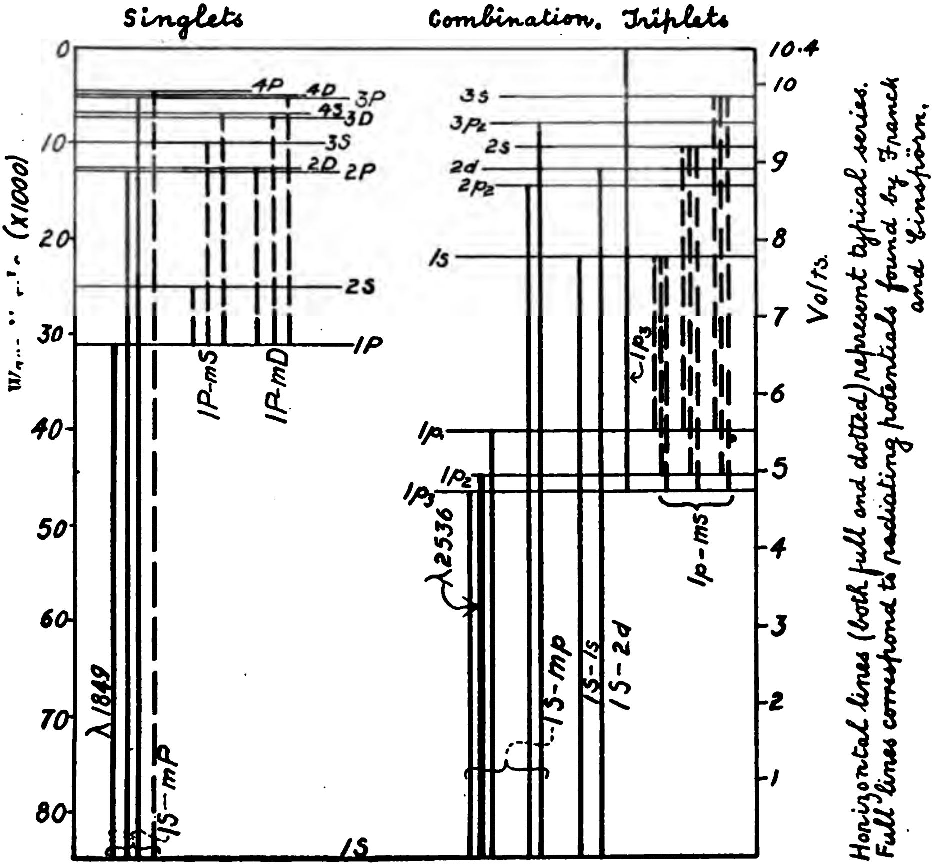

FIG. 25.

frequency difference between each orbit and consequently the energy necessary to shift an electron from any orbit to any other. The left boundary of the diagram is in the 1S orbit, the outermost orbit occupied by an electron in the normal atom. The right boundary corresponds to an orbit at infinity, and the distance between the boundaries measures the ionizing potential. The horizontal lines (whose length is a wave number) correspond to spectral lines denoted by the position of their ends. Thus four lines in the principal series 1S — mP are shown. The full lines shown in the diagram are those which probably correspond to the radiating potentials found by Franck and Einspörn.. (The dotted lines illustrate other lines belonging to a few of the well-known series of mercury.)

CUMULATIVE EFFECTS—LOW VOLTAGE ARCS

In this section will be considered a group of investigations on the phenomena which only become evident when sufficiently dense electron streams are passed through a gas, and whose density is usually appreciable. In the foregoing sections, attention has chiefly been paid to those results which bear out the quantum relations. But certain investigations have been published, which, at first sight, seem in conflict with the results expected from theory, and confirmed by other researches. In general, these effects come into play only when the impact of an electron on a molecule can no longer be regarded as an isolated event, that is, when the result of an impact is not influenced by the radiation to which the molecule is exposed from other impacts in its vicinity, and by impacts which it may have experienced a short time previously.

As the supply of electrons is increased when electrons are driven through a gas at a low voltage (provided pressure and voltage are suitable) a more or less visible discharge (an arc) may suddenly set in, a large increase in the current occurring simultaneously. This increase in current indicates ionization. It became evident, however, that a voltage much less than the ionizing potential would produce an arc under favorable conditions, thus throwing doubt on whether any fundamental importance could be attached to the so-called ionizing potentials.

Richardson and Bazzoni[1] found that with an intense electron stream through helium, an arc could be made to strike when the potential accelerating the electrons was as low as 22.5 volts and mentioned that there were indications that the striking potential tended to still smaller values. Hebb[2] found that a mercury arc could be started with electrons whose velocities correspond to 4.7 volts only, and that it could be maintained at 3.2 volts. Later,[3] he maintained that Hg was directly ionized by electrons of 4.9 volts velocity and that no explanation of the effect as a secondary phenomenon could be considered adequate. In another research[1] on arcs in mixtures of K and Hg and of Na and Hg, he found that an arc could be struck in the former at 1.6 volts and in the latter at 2.5 volts and maintained in them at .5 and 1.4 volts, respectively. In the case of the arc in the mixture of Hg and K vapors, it is interesting to note that even when the electrons had a velocity of only .5 volt, the mercury spectrum was visible. This value, .5 volt, as well as the 1.4 volt, at which the arc was started, is, of course, much below the ionizing and radiating potentials of Hg. Very recently Hebb[2] concluded that ionization of Hg vapor can take place at potentials as low as 3.2 volts, with very intense electron streams, and that the previous limit given for ionization, viz., 4.9 volts, has no special significance. Tate[3] showed that with large electron streams through Hg vapor, arcs could be started with velocities down to 7.3 volts. McLennan[4] found that the potentials at which arcs would strike depended very much on the density of the electron stream, and the density of the vapor, decreasing as these factors increased. With Hg and Cd, the lowest potentials, under the most favorable conditions at which arcs could be struck, were 4.75 and 5 volts, respectively, while they could be maintained at potentials as low as 2.84 and 2.0 volts. It was recorded that close to these minimum striking potentials the arc took an appreciable time to start, after the potential was applied. It should be noted that time lag effects, of which this is one, have frequently been observed in connection with phenomena associated with intense electron currents through gases.[5]

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[1] *Nature*, 48, 5 (1916).

[2] *P. R.*, 9, 371 (1917).

[3] *Ibid.*, 11, 170 (1918).

As will be seen from the table, several investigators have found strong ionization in helium and argon at potentials at which other experimenters find radiation only. (In the experiments showing ionization, dense electron currents and appreciable pressures were used.) Compton, Olmstead, and Lilly[6] found that with a sufficiently dense stream of electrons in He at a suitable pressure, arcs could be started at a potential as low as 20.2 volts, *i. e.*, the radiating potential, and could be maintained at still lower potentials, 8 volts being the lowest. However, no further decrease in the striking potential (20.2 volts) could be obtained by any further increase in the density of the electron stream or change in pressure. It would appear that these experiments definitely prove that the radiating potential in helium is the lowest potential at which ionization can be started, even under the most favorable conditions, a result which is in agreement with McLennan's results, and with Hebb's earlier results.

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[1] *P. R.*, **12**, 486 (1918).

[2] *Ibid.*, **15**, 130 (1920).

[3] *Ibid.*, **10**, 81 (1917).

[4] *P. L. P. S.*, **31**, 1 (1918).

[5] Richardson and Bazzoni, *P. M.*, **32**, 426 (1916); Tate, *P. R.*, **10**, 81 (1917); Compton, Lilly and Olmstead, *Ibid.*, **15**, 545 (1920).

[6] *P. R.*, **15**, 545 (1920).

Various explanations of these apparently anomalous effects with dense electron streams through gases at appreciable pressures have been offered. Richardson and Bazzoni[1] suggest that ionization at potentials lower than those corresponding to the theoretical ionizing potential is the result of successive impacts, or results from impacts on atoms in an abnormal condition caused by the absorption of radiation generated in other atoms.

Millikan[2] suggested that just above the radiating potential (this term was not in use at the time), 4.9 volts for Hg, the radiation (λ 2536) produced might act photo-electrically on the neighboring atoms, certainly those of the cathode and possibly those of the surrounding vapor, and thus add more electrons to the original stream. The electrons so produced would be accelerated by the field and might produce, if favorably placed, more radiation, which, in turn, would release more electrons photo-electrically. In this way, it could be readily seen how an indefinite multiplication of the original electron current might occur, and how ionization would accompany the radiation produced at 4.9 volts. The most important feature of Millikan's theory is that charged atoms resulting from the expulsion of the photo-electrons would permit (1) ionization, (2) the many-lined spectrum, and (3) the low voltage arc, all below the accepted ionizing potential 10.4 volts. This follows from the fact that an atom which had lost an electron photo-electrically would sometime later regain an electron, and this would pass from one Bohr orbit to another on its way to the orbit which it would finally occupy in the normal atom. In jumping from one orbit to another radiation of the corresponding wavelength would be given out, and thus the production of the many-lined spectrum could easily be accounted for. Also, it would need but very little energy on the part of an impinging electron to ionize an atom in which the electron happened to be in one of the outer orbits while on its way inwards to the orbit normally occupied. Thus ionization of abnormal atoms was accounted for—hence low voltage arcs. Atoms in all stages of recovery to normal would be found, and the effects (1), (2) and (3) would be weak or strong according as few or many of the outer orbits were occupied by electrons. The minimum striking potential for the arc (4.9 volts) was taken to show that the outermost orbit occupied in the normal Hg atom was the one corresponding to the limit of the series of which λ 2536 is the first member, for, unless the impinging electron has sufficient energy to displace an electron to the next possible orbit, no radiation (and ionization resulting therefrom) can possibly occur. Though it is now evident that λ 2536 cannot ionize Hg vapor, Millikan's theory would still hold if, for the *complete* ionization of the Hg atom photo-electrically, one substituted *partial* ionization, *i. e.*, the displacement of the electron from the normal orbit 1S to the $1p_2$ orbit, in which state the atom could be ionized by subsequent impacts of electrons with energy well below 10.4 volts.

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[1] *Nature*, 48, 5 (1916).

[2] *P. R.*, 9, 378 (1917).

Van der Bijl[1] suggested that the production of ionization, the many-lined spectrum, and arcs with potentials below the ionizing potential, could be accounted for on the assumption that with dense electron streams an atom would frequently experience a second collision while still in an abnormal state resulting from a previous collision. Thus if we have a stream of electrons with energy corresponding to 5 or 6 volts passing through Hg vapor, the first collision with an atom will displace an electron from the normal orbit to the orbit $1p_2$. The atom is now in a state that needs but $10.4 - 4.9 = 5.5$ volts to remove the electron, so that a second collision may effect complete ionization. The idea here involved is frequently referred to as that of *successive* impacts.

McLennan[2] attributed the production of "faint arcs" showing the many-lined spectrum, at potentials much below the ionizing potential, to the presence of electrons of abnormal velocities among those emitted by the incandescent source. In one case, electrons of initial energy corresponding to 5 volts would have to be assumed. For these arcs, it was suggested that the direct action of the few high speed electrons would be sufficient. (A calculation of the proportion of electrons having such high speeds from any thermal source, however, shows it to be negligibly small.) In the case of "brilliant arcs" McLennan considers that some other consideration (*e. g.*, the part played by positive ions) must be taken into account, high speed electrons alone being inadequate to account for the results.

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[1] *P. R.*, **10**, 546 (1917).

[2] *P. L. P. S.*, **31**, 1 (1918).

Compton[1] investigated whether the theory of successive impacts was adequate to explain the experimental effects. His calculations hinge upon the average time interval in which an atom can remain in an abnormal state. Unfortunately, this is not known for Hg, but use was made of Stark's value, 6×10^{-7} sec. for hydrogen, as a tentative assumption. His conclusion is that the effect of successive impacts may in some cases be sufficient to account for the phenomena, but that, in general, it is insufficient to account for all the observed phenomena. The cumulative effect of absorbed radiation and direct impact may be more important.*

Compton[2] has recently made quantitative measurements of the amount of ionization which accompanies radiation in He produced by electrons whose energy is between the radiating potential and the ionizing potential. These experiments are of importance in that they indicate clearly the source of conflicting results on the presence of ionization below the ionizing potential. The arrangement shown in fig. 20 was used. From the ratios of the effects obtained when the gauze side and when the plate side of the cylinder faced the electron stream the ratio of the ionization effect to the radiation effect could be obtained. From 20 volts to 25 volts (fig. 21) this ratio was a constant in any particular case and decreased abruptly at 25 volts, because direct ionization set in. The following are the results obtained at various pressures with electron currents of the order of 10^{-6} amperes:

Pressure Mm.	$\frac{\text{Ionization}}{\text{Radiation}}$ (below I. P.)
0.0005	0.055
0.003	0.176
0.082	0.333
0.044	0.410
1.0	2.22
25.0	11.4

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[1] *P. R.*, 15, 130, 476 (1920).

* In view of the suggestion (discussed above), put forward by Franck and Knipping, that atoms in pure helium can be put into an abnormal state by collision with 20.45 volt electrons, and show no tendency to return to the normal state, it may be that "successive impacts" will account for much more of the cumulative effects than would be expected on the assumption that the abnormal state lasts only about 6×10^{-7} sec.

[2] *P. M.*, 40, 553 (1920).

It will be seen that at higher pressures ionization predominates, and is present even at the lowest pressure. When the pressure is constant and the electric current is increased the ratio also increases but not much, showing that the cumulative effect of successive impacts is not so important as the cumulative effect of absorption of radiation and a direct impact.

Horton and Bailey[1] believe that their results show that when there is ionization in helium below 25 volts, it is due to ionization of the impurities (*e. g.*, Hg) by the 20 volt radiation from the helium. While their experiments certainly show that apparently negligible traces of impurities produce large ionization effects, Compton's results cannot be accounted for as an impurity effect. Reasons in support of this are given in Compton's paper. Perhaps the clearest proof of the existence of ionization in helium below 25.5 volts is the striking of an arc in the purest helium at 20.2 volts, an effect which is too big to be accounted for by traces of impurities.

Compton's view of the cumulative effect of absorbed radiation and direct impact has been strengthened by some very recent experiments of Compton and Smyth[2] in which it was found that the ionizing potential of fluorescing iodine vapor was lower than that of normal iodine vapor. For normal iodine vapor, the value was about 10 volts, while for iodine vapor made fluorescent by green light (corresponding potential 2.3 volts), the value was 7.5 volts, just 2.5 volts less.

An interesting illustration of cumulative effects appears in the recent work of Compton, Lilly and Olmstead.[3] They found that in the helium arc all the ordinary lines appear simultaneously when the arc strikes. As we have seen, in order that the arc shall strike, there must be ionization, and when this takes place below 25.5 volts, it cannot be anything else but a cumulative effect. There will be electrons in all the outer orbits dropping step by step towards the inner orbits thus emitting lines in the visible as well as the ultraviolet region. When the arc is intense, few of them will get to the normal position as the frequent electron collisions re-eject them. The *enhanced* line λ 4686 belongs to the *charged* helium atom, and is denoted in Bohr's notation as $4N \{1/3^2 - 1/4^2\}$. It cannot be produced until a helium atom already deprived of one electron is disturbed. As the formula shows it is emitted when the electron drops back from orbit 4 to orbit 3, in the *charged* atom (fig. 26). It can be produced in two different ways, the first being found when the electrons in the electron stream have sufficient energy to detach *both* electrons from the atom. This corresponds to the ionizing potential 80 volts (see table on p. 142). In agreement with this, the authors found that the enhanced line λ 4686 suddenly appeared when the potential across the arc was raised to 80 volts (the gas pressure being low and the thermionic current not intense). With higher pressure and more intense currents, the line becomes visible at 55 volts. This was explained as a cumulative effect, one example of which is the removal of the first electron from the atom and a collision between the charged atom and an electron of sufficient energy to lift the remaining electron from orbit 1 to orbit 4 or any orbit beyond. (The diagram shows that the minimum energy required is 50.72 volts.) Other combinations forming cumulative effects are given in the paper.

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[1] *P. M.*, **40**, 440 (1920).

[2] *Science*, **51**, 571, June 4 (1920).

[3] *P. R.*, **16**, 282 (1920).

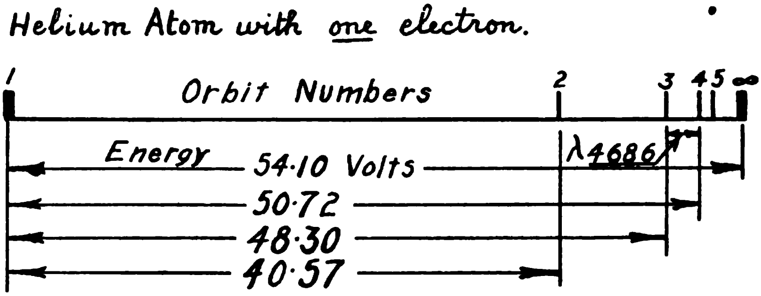

Fig. 26.

Compton's results on ionization in helium between the ionizing and radiating potentials open up interesting considerations as to similar phenomena in other gases. To account for ionization of helium atoms just above the radiating potential, the ionization must be a second "event" in the recent history of the atom, the first being the absorption of energy, 20.4 volts, to make the atom an abnormal one, either through an earlier impact, or, more probably, through the absorption of radiant energy from neighboring atoms. As the energy required to remove the electron completely from an abnormal atom is 25.3 — 20.4 = 4.9 volts, there is energy to spare in the 20.4 volt electron stream for the "second event." But this is not the case for elements in which the ionizing potential is more than twice the radiating potential. We may cite mercury vapor (4.9 volts and 10.4 volts), and still more to the point, iodine vapor (2.34 volts and 10.1 volts). Electrons of velocity just above 4.9 volts would be unable to ionize a mercury atom as a result of two "events;" it would appear that three "events" would be necessary. Presumably a mercury atom cannot acquire any more energy than 4.9 volts, through the absorption of 4.9 volt radiation (λ 2536) no matter how intense (as radiation of different wave-length corresponds to removal from 2nd to 3rd orbit), hence, it would appear that the second and third events would have to be successive impacts. Investigation on these lines should lead to important results.

COMPOUND GASES

Investigations of the critical potentials for compounds should furnish evidence as to the mode in which atoms are bound together in a compound. The first critical potentials for a number of compounds were determined by Hughes and Dixon[1] (see table p. 136.) No general conclusions could be drawn, except that the first critical potentials for CH_4, C_2H_6, C_2H_4, C_2H_2 were very much the same. It is desirable that these compounds be re-examined on the lines of the best of the recent investigations to obtain accurate values for the radiating and ionizing potentials and to distinguish between them.

Several important theoretical papers by Born[2] and Fajans[3] have appeared on the affinity of the halogen atoms for electrons, and on the ionizing potentials of HCl, HBr and HI. The line of argument may very briefly be outlined as follows. Born regards a crystal such as KCl as being held together by forces between the positive K ion and the negative Cl ion. His theory gives a value, U_{KCl}, for the work necessary to dissociate the crystal into gaseous K_+ and Cl_- ions. This final stage can be arrived at in another way. Imagine the crystal to be dissociated into potassium (metal) and chlorine gas, and then the potassium to be vaporized and afterwards ionized into K_+ and free electrons, while the chlorine gas Cl_2 is dissociated into atomic Cl and afterwards the Cl atoms unite with the free electrons to form Cl_- ions. The energies required are, respectively, Q_{KCl}, the ordinary heat of combination; D_K, the heat of vaporization of K; J_K, the work of ionization of K;

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[1] *P. R.*, 10, 495 (1917).

[2] *V. d. D. P. G.*, 21, 13, 679 (1919).

[3] *Ibid.*, 21, 714 (1919).

D_{Cl}^{4}, the heat of dissociation of Cl_2; and E_{Cl}, the energy *given out* when a Cl atom combines with an electron.

$$U_{KCl} = Q_{KCl} + D_K + J_K + D_{Cl} - E_{Cl}$$

All the values are known except E_{Cl} which turns out to be 5.16 volts. This means that energy is *given out* when a negative Cl ion is formed, *i. e.*, Cl– is *stable.*

If the ionization of HCl is merely the disruption of the molecule into H+ and CL–, the energy necessary to effect it, J_{HCl}, can be predicted according to Born and Fajans. The decomposition of HCl into H_2 and Cl_2 requires an amount of energy Q_{HCl} (the ordinary heat of formation); the dissociation of H_2 into H requires an amount of energy D_H; of Cl_2 into Cl, an amount D_{Cl}; the ionization of atomic H into H+ and free electrons requires an amount J_H (given by the ionizing potential 13.52 volts); and the union of Cl with a free electron corresponds to the evolution of heat E_{Cl}. Hence,

$$J_{HCl} = Q_{HCl} + D_H + D_{Cl} + J_H - E_{Cl}$$

If E_{Cl} be taken to be 5.16 volts, then J_{HCl} will have a value of 13.9 volts.

This was tested experimentally by Foote and Mohler[1] who obtained a value of 13.7 volts for the ionizing potential of HCl. This, then, may be regarded as confirming the view of Born and Fajans as to the mechanism of ionization of HCl. It should be mentioned that Hughes and Dixon[2] found a critical potential in HCl at about 9.5 volts (together with evidence of a much stronger ionization at about 13 volts) which may, of course, be a radiating potential. Foote and Mohler, however, state that they have found no evidence of a radiating potential.

A useful discussion of the values of the ionizing potential to be expected for certain compounds has been given by Foote and Mohler.[3] The compounds considered are those for which there is reason to believe that ionization takes the form of splitting up the molecule into positively and negatively charged atoms, and for which there is sufficient thermochemical data to predict the value of the ionizing potential. The results are arrived at on lines more or less similar to those used in the last paragraph for HCl.

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[1] *J. A. C. S.*, **42**, 1832 (1920).

[2] *P. R.*, **10**, 495 (1917).

[3] *Jour. Wash. Acad. Sci.*, **10**, 435 (1920).

APPENDIX

(Added after the report was in type—March, 1921)

I. The principal critical potentials for many metallic vapors have now been shown to be associated, through the quantum relation ($Ve = h\nu$) with lines in certain series in their spectra. These lines are $1S - 1p_2$, $1S - 1P$, and the limit 1S, for the metals of the second column of the periodic table, and the doublet $1\sigma - 1\pi$ and the corresponding limit 1σ for the alkali metals. Once the identity of this relation is admitted, much more accurate values of the critical potentials can be calculated from spectroscopic data than can be obtained by direct experiment. Professor F. A. Saunders kindly furnished the data for the alkali metals. The data for the other metals were obtained from a recent paper by Mohler, Foote, and Meggers (Bur. Standards, *Sci. Papers* No. **403,** 1920). It should be mentioned that, in this paper, it has been shown experimentally that each element (in the second column of the periodic table) investigated, has two well-marked radiating potentials and one ionizing potential. This result is valuable in showing the uniformity of the elements in this group with respect to the critical potentials, a result which was expected, but had not been demonstrated. (The calculated potentials are given to four significant figures only, as h and e are not known to less than 1 in 1000.)

Metal	Series	Wave-length	Calculated Potential	
			Ionizing	Radiating
Mercury	1S	1187.96	10.392	...
	$1S - 1p_2$	2537.48	....	4.865
	$1S - 1P$	1849.60	....	6.674
Cadmium	1S	1378.69	8.954	...
	$1S - 1p_2$	3262.09	....	3.784
	$1S - 1P$	2288.79	....	5.394
Zinc	1S	1319.98	9.352	...
	$1S - 1p_2$	3076.88	....	4.012
	$1S - 1P$	2139.33	....	5.770
Magnesium	1S	1621.72	7.612	...
	$1S - 1p_2$	4572.65	....	2.700
	$1S - 1P$	2853.06	....	4.327
Barium	1S	2379.28	5.188	...
	$1S - 1p_2$	7913.52	....	1.560
	$1S - 1P$	5537.04	....	2.229
Strontium	1S	2176.94	5.671	...
	$1S - 1p_2$	6894.45	....	1.791
	$1S - 1P$	4608.61	....	2.679

Calcium	$1S$	2028.20	6.087	...
	$1S - 1p_2$	6574.59	....	1.878
	$1S - 1P$	4227.91	....	2.920
Caesium	1σ	3191.37	3.873	...
	$1\sigma - 1\pi$	8523.33	....	1.447
		8945.82	....	1.378
Rubidium	1σ	2968.70	4.154	...
	$1\sigma - 1\pi$	7802.39	....	1.580
		7949.76	....	1.551
Potassium	1σ	2856.76	4.317	...
	$1\sigma - 1\pi$	7666.95	....	1.608
		7701.13	....	1.601
Sodium	1σ	2412.84	5.111	...
	$1\sigma 1 - \pi$	5891.78	....	2.093
		5897.76	....	2.091
Lithium	1σ	2299.67	5.362	...
	$1\sigma - 1\pi$	6709.94	....	1.838
		6710.08	....	1.838

II. Attention is drawn to the following recent papers bearing on "Photo-Electricity."

Foote and Mohler, *P. R.*, **17,** 394(1921), find the following ionizing and radiating potentials.

	R. P.	I. P.
Zinc ethyl	7 volts	12 volts
Zinc chloride	....	12.9 volts
Mercuric chloride	....	12.1 volts
Carbon monoxide	....	10.1 volts
		14.3 volts

Joly, *P. M.*, **41,** 289 (1921) and Poole, *P. M.*, **41,** 347 (1921), discuss the application of photo-electricity and the quantum theory to vision. Experiments on the photo-electric effect of the active materials of the retina are described.

Stebbins, *A. P. J.*, **53,** 105 (1921), employed a photo-electric cell to study the fluctuations of the star Algol.

Angerer, *P. Z.*, **22,** 98 (1921), made use of a photo-electric cell to study the after glow in active nitrogen. In connection with the point raised by Elster and Geitel (p. 107), Angerer was able to study rather rapid changes of light intensity satisfactorily.

Sir J. J. Thomson, *P. M.*, **41,** 526 (1921), calculated the ionizing potentials for a number of elements on the basis of his theory of the atom. The ratio of the ionizing potential for Li to that for H is of the right order; the ionizing potential for Na appears to be considerably smaller than the experimental value. The theoretical values for O and N cannot be compared directly with the experimental values which relate to O_2 and N_2.

A good discussion of critical potentials with reference to the Bohr type of atom will be found in Sommerfeld's "Atombau und Spektrallinien" (2nd edition). (The writer was unable to get a copy in time to make use of it in drawing up the report.)

A full account of the work on hydrogen referred to on p. 139 under the names of Franck, Knipping and Kruger will be found in an article by Kruger in *A. d. P.*, **64**, 288 (1921).

Hodgman, *P. R.*, **17**, 246 (1921), gives a list of color filters (dyes in gelatine) with transmission ranges (mainly in the visible), which may prove useful in photo-electric experiments. Data regarding the transmission of various colored glasses for use in securing monochromatic light when used in conjunction with the mercury arc, or the discharge in hydrogen or helium will be found in Technologic Paper No. **148**, 1920 of the Bureau of Standards.

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THE SCALE OF THE UNIVERSE*

PART I
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PART II
BY HEBER D. CURTIS
Director, Allegheny Observatory

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PART I

BY HARLOW SHAPLEY

EVOLUTION OF THE IDEA OF GALACTIC SIZE

The physical universe[1] was anthropocentric to primitive man. At a subsequent stage of intellectual progress it was centered in a restricted area on the surface of the earth. Still later, to Ptolemy and his school, the universe was geocentric; but since the time of Copernicus the sun, as the dominating body of the solar system, has been considered to be at or near the center of the stellar realm. With the origin of each of these successive conceptions, the system of stars has ever appeared larger than was thought before. Thus the significance of man and the earth in the sidereal scheme has dwindled with advancing knowledge of the physical world, and our conception of the dimensions of the discernible stellar universe has progressively changed. Is not further evolution of our ideas probable? In the face of great accumulations of new and relevant information can we firmly maintain our old cosmic conceptions?

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*This address and the following one by Dr. Heber D. Curtis are adapted from illustrated lectures given on the William Ellery Hale Foundation before the National Academy of Sciences, April 26, 1920. The authors have exchanged papers in preparing them for publication in order that each might have the opportunity of considering the point of view of the other.

[1] The word "universe" is used in this paper in the restricted sense, as applying to the total of sidereal systems now known to exist.

As a consequence of the exceptional growth and activity of the great observatories, with their powerful methods of analyzing stars and of sounding space, we have reached an epoch, I believe, when another advance is necessary; our conception of the galactic system must be enlarged to keep in proper relationship the objects our telescopes are finding; the solar system can no longer maintain a central position. Recent studies of clusters and related subjects seem to me to leave no alternative to the belief that the galactic system is at least ten times greater in diameter—at least a thousand times greater in volume—than recently supposed.

Dr. Curtis,[1] on the other hand, maintains that the galactic system has the dimensions and arrangement formerly assigned it by students of sidereal structure—he supports the views held a decade or so ago by Newcomb, Charlier, Eddington, Hertzsprung, and other leaders in stellar astronomy. In contrast to my present estimate of a diameter of at least three hundred thousand light-years Curtis outlines his position as follows:[2]

> As to the dimensions of the galaxy indicated by our Milky Way, till recently there has been a fair degree of uniformity in the estimates of those who have investigated the subject. Practically all have deduced diameters of from 7,000 to 30,000 light-years. I shall assume a maximum galactic diameter of 30,000 light-years as representing sufficiently well this older view to which I subscribe though this is pretty certainly too large.

I think it should be pointed out that when Newcomb was writing on the subject some twenty years ago, knowledge of those special factors that bear directly on the size of the universe was extremely fragmentary compared with our information of to-day.

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[1] See Part II of this article, by Heber D. Curtis.

[2] Quoted from a manuscript copy of his Washington address.

In 1900, for instance, the radial motions of about 300 stars were known; now we know the radial velocities of thousands. Accurate distances were then on record for possibly 150 of the brightest stars, and now for more than ten times as many. Spectra were then available for less than one-tenth of the stars for which we have the types to-day. Practically nothing was known at that time of the photometric and spectroscopic methods of determining distance; nothing of the radial velocities of globular clusters or of spiral nebulae, or even of the phenomenon of star streaming.

As a further indication of the importance of examining anew the evidence on the size of stellar systems, let us consider the great globular cluster in Hercules—a vast sidereal organization concerning which we had until recently but vague ideas. Due to extensive and varied researches, carried on during the last few years at Mount Wilson and elsewhere, we now know the positions, magnitudes, and colors of all its brightest stars, and many relations between color, magnitude, distance from the center, and star density. We know some of these important correlations with greater certainty in the Hercules cluster than in the solar neighborhood. We now have the spectra of many of the individual stars, and the spectral type and radial velocity of the cluster as a whole. We know the types and periods of light variation of its variable stars, the colors and spectral types of these variables, and something also of the absolute luminosity of the brightest stars of the cluster from the appearance of their spectra. Is it surprising, therefore, that we venture to determine the distance of Messier 13 and similar systems with more confidence than was possible ten years ago when none of these facts was known, or even seriously considered in cosmic speculations?

If he were writing now, with knowledge of these relevant developments, I believe that Newcomb would not maintain his former view on the probable dimensions of the galactic system.

For instance, Professor Kapteyn has found occasion, with the progress of his elaborate studies of laws of stellar luminosity and density, to indicate larger dimensions of the galaxy than formerly accepted. In a paper just appearing as *Mount Wilson Contribution*, No. 188,[1] he finds, as a result of the research extending over some 20 years, that the density of stars along the galactic plane is quite appreciable at a distance of 40,000 light-years—giving a

[1] The *Contribution* is published jointly with Dr. van Rhijn.

diameter of the galactic system, exclusive of distant star clouds of the Milky Way, about three times the value Curtis admits as a maximum for the entire galaxy. Similarly Russell, Eddington, and, I believe, Hertzsprung, now subscribe to larger values of galactic dimensions; and Charlier, in a recent lecture before the Swedish Astronomical Association, has accepted the essential features of the larger galaxy, though formerly he identified the local system of B stars with the whole galactic system and obtained distances of the clusters and dimension of the galaxy only a hundredth as large as I derive.

SURVEYING THE SOLAR NEIGHBORHOOD

Let us first recall that the stellar universe, as we know it, appears to be a very oblate spheroid or ellipsoid—a disk-shaped system composed mainly of stars and nebulae. The solar system is not far from the middle plane of this flattened organization which we call the galactic system. Looking away from the plane we see relatively few stars; looking along the plane, through a great depth of star-populated space, we see great numbers of sidereal objects constituting the band of light we call the Milky Way. The loosely organized star clusters, such as the Pleiades, the diffuse nebulae such as the great nebula of Orion, the planetary nebulae, of which the ring nebula in Lyra is a good example, the dark nebulosities—all these sidereal types appear to be a part of the great galactic system, and they lie almost exclusively along the plane of the Milky Way. The globular clusters, though not in the Milky Way, are also affiliated with the galactic system; the spiral nebulae appear to be distant objects mainly if not entirely outside the most populous parts of the galactic region.

This conception of the galactic system, as a flattened, watch-shaped organization of stars and nebulae, with globular clusters and spiral nebulae as external objects, is pretty generally agreed upon by students of the subject; but in the matter of the distances of the various sidereal objects—the size of the galactic system—there are, as suggested above, widely divergent opinions. We shall, therefore, first consider briefly the dimensions of that part of the stellar universe concerning which there is essential unanimity of opinion, and later discuss in more detail the larger field,

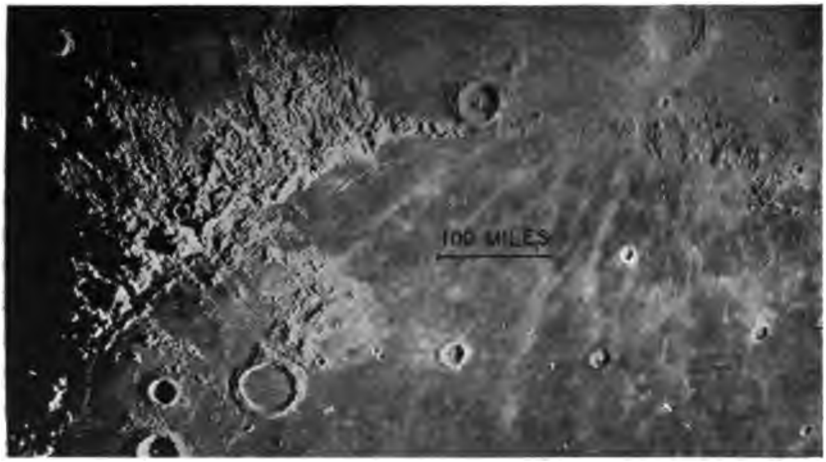

FIG. 1.—The region of the Apennines on the surface of the moon as photographed with the 100-inch reflector. Photograph by F. G. Pease.

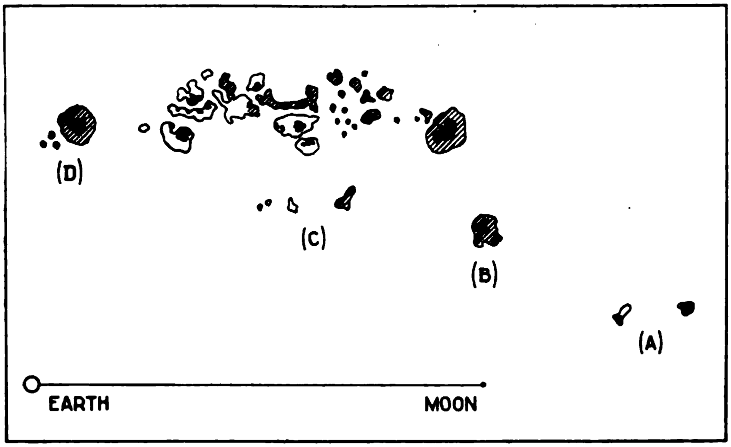

FIG. 2.—A group of sun-spots first appearing in February 1920 and lasting for about 100 days. The shaded and unshaded regions indicate magnetic polarities of opposite signs. Drawing by S. B. Nicholson.

FIG. 3.—Two successive photographs on the same plate of the diffuse nebula N. G. C. 221, made with the 100-inch reflector to illustrate the possibility of greatly increasing the photographic power of a large reflector through the use of accessory devices. The exposure time for the picture on the left was fifteen minutes; it was five minutes for the picture on the right, which was made with the aid of the photographic intensifier described in *Proc. Nat. Acad. Sci.*, 6, 127, 1920. In preparing the figure the two photographs were enlarged to the same scale.

where there appears to be a need for modification of the older conventional view.

Possibly the most convenient way of illustrating the scale of the sidereal universe is in terms of our measuring rods, going from terrestrial units to those of stellar systems. On the earth's surface we express distances in units such as inches, feet, or miles. On the moon, as seen in the accompanying photograph made with the 100-inch reflector, the mile is still a usable measuring unit; a scale of 100 miles is indicated on the lunar scene.

Our measuring scale must be greatly increased, however, when we consider the dimensions of a star—distances on the surface of our sun, for example. The large sun-spots shown in the illustration cannot be measured conveniently in units appropriate to earthly distance—in fact, the whole earth itself is none too large. The unit for measuring the distances from the sun to its attendant planets, is, however, 12,000 times the diameter of the earth; it is the so-called astronomical unit, the average distance from earth to sun. This unit, 93,000,000 miles in length, is ample for the distances of planets and comets. It would probably suffice to measure the distances of whatever planets and comets there may be in the vicinity of other stars; but it, in turn, becomes cumbersome in expressing the distances from one star to another, for some of them are hundreds of millions, even a thousand million, astronomical units away.

This leads us to abandon the astronomical unit and to introduce the light-year as a measure for sounding the depth of stellar space. The distance light travels in a year is something less than six million million miles. The distance from the earth to the sun is, in these units, eight light-minutes. The distance to the moon is 1.2 light-seconds. In some phases of our astronomical problems (studying photographs of stellar spectra) we make direct microscopic measures of a ten-thousandth of an inch; and indirectly we measure changes in the wave-length of light a million times smaller than this; in discussing the arrangement of globular clusters in space, we must measure a hundred thousand light-years. Expressing these large and small measures with reference to the velocity of light, we have an illustration of the scale of the astronomer's universe—his measures range from the trillionth of a billionth part of one light-second, to more than a thousand light-centuries. The ratio of the greatest measure to the smallest is as 10^{33} to 1.

It is to be noticed that light plays an all-important rôle in the study of the universe; we know the physics and chemistry of stars only through their light, and their distance from us we express by means of the velocity of light. The light-year, moreover, has a double value in sidereal exploration; it is geometrical, as we have seen, and it is historical. It tells us not only how far away an object is, but also how long ago the light we examine was started on its way. You do not see the sun where it is, but where it was eight minutes ago. You do not see faint stars of the Milky Way as they are now, but more probably as they were when the pyramids of Egypt were being built; and the ancient Egyptians saw them as they were at a time still more remote. We are, therefore, chronologically far behind events when we study conditions or dynamical behavior in remote stellar systems; the motions, light-emissions, and variations now investigated in the Hercules cluster are not contemporary, but, if my value of the distance is correct, they are the phenomena of 36,000 years ago. The great age of these incoming pulses of radiant energy is, however, no disadvantage; in fact, their antiquity has been turned to good purpose in testing the speed of stellar evolution, in indicating the enormous ages of stars, in suggesting the vast extent of the universe in time as well as in space.

Taking the light-year as a satisfactory unit for expressing the dimensions of sidereal systems, let us consider the distances of neighboring stars and clusters, and briefly mention the methods of deducing their space positions. For nearby stellar objects we can make direct trigonometric measures of distance (parallax), using the earth's orbit or the sun's path through space as a base line. For many of the more distant stars spectroscopic methods are available, using the appearance of the stellar spectra and the readily measurable apparent brightness of the stars. For certain types of stars, too distant for spectroscopic data, there is still a chance of obtaining the distance by means of the photometric method. This method is particularly suited to studies of globular clusters; it consists first in determining, by some means, the real luminosity of a star, that is, its so-called absolute magnitude, and second, in measuring its apparent magnitude. Obviously, if a star of known real brightness is moved away to greater and greater distances, its apparent brightness decreases; hence, for such stars of known absolute magnitude, it is possible, using a simple formula, to determine the distance by measuring the apparent magnitude.

It appears, therefore, that although space can be explored for a distance of only a few hundred light-years by direct trigonometric methods, we are not forced, by our inability to measure still smaller angles, to extrapolate uncertainly or to make vague guesses relative to farther regions of space, for the trigonometrically determined distances can be used to calibrate the tools of newer and less restricted methods. For example, the trigonometric methods of measuring the distance to moon, sun, and nearer stars are decidedly indirect, compared with the linear measurement of distance on the surface of the earth, but they are not for that reason inexact or questionable in principle. The spectroscopic and photometric methods of measuring great stellar distance are also indirect, compared with the trigonometric measurement of small stellar distance, but they, too, are not for that reason unreliable or of doubtful value. These great distances are not extrapolations. For instance, in the spectroscopic method, the absolute magnitudes derived from trigonometrically measured distances are used to derive the curves relating spectral characteristics to absolute magnitude; and the spectroscopic parallaxes for individual stars (whether near or remote) are, almost without exception, interpolations. Thus the data for nearer stars are used for purposes of calibration, not as a basis for extrapolation.

By one method or the other, the distances of nearly 3,000 individual stars in the solar neighborhood have now been determined; only a few are within ten light-years of the sun. At a distance of about 130 light-years we find the Hyades, the well known cluster of naked eye stars; at a distance of 600 light-years, according to Kapteyn's extensive investigations, we come to the group of blue stars in Orion—another physically-organized cluster composed of giants in luminosity. At distances comparable to the above values we also find the Scorpio-Centaurus group, the Pleiades, the Ursa Major system.

These nearby clusters are specifically referred to for two reasons.

In the first place I desire to point out the prevalence throughout all the galactic system of clusters of stars, variously organized as to stellar density and total stellar content. The gravitational organization of stars is a fundamental feature in the universe—a double star is one aspect of a stellar cluster, a galactic system is another. We may indeed, trace the clustering motive from the richest of isolated globular clusters such as the system in Hercules, to the loosely organized nearby groups typified in the bright stars of Ursa Major. At one hundred times its present distance, the Orion cluster would look much like Messier 37 or Messier 11; scores of telescopic clusters have the general form and star density of the Pleiades and the Hyades. The difference between bright and faint clusters of the galactic system naturally appears to be solely a matter of distance.

In the second place I desire to emphasize the fact that the nearby stars we use as standards of luminosity, particularly the blue stars of spectral type B, are members of stellar clusters. Therein lies a most important point in the application of photometric methods. We might, perhaps, question the validity of comparing the isolated stars in the neighborhood of the sun with stars in a compact cluster; but the comparison of nearby cluster stars with remote cluster stars is entirely reasonable, since we are now so far from primitive anthropocentric notions that it is foolish to postulate that distance from the earth has anything to do with the intrinsic brightness of stars.

ON THE DISTANCES OF GLOBULAR CLUSTERS

1. As stated above, astronomers agree on the distances to the nearby stars and stellar groups—the scale of the part of the universe that we may call the solar domain. But as yet there is lack of agreement relative to the distances of remote clusters, stars, and star clouds—the scale of the total galactic system. The disagreement in this last particular is not a small difference of a few percent, an argument on minor detail; it is a matter of a thousand percent or more.

Curtis maintains that the dimensions I find for the galactic system should be divided by ten or more (see quotation on page 172); therefore, that galactic size does not stand in the way of interpreting spiral nebulae as comparable galaxies (a theory that he favors on other grounds but considers incompatible with the larger values of galactic dimensions). In his Washington address, however, he greatly simplified the present discussion by accepting the results of recent studies on the following significant points:

Proposition A.—The globular clusters form a part of our galaxy; therefore the size of the galactic system proper is most probably not less than the size of the subordinate system of globular clusters.

Proposition B.—The distances derived at Mount Wilson for globular clusters *relative to one another* are essentially correct. This implies among other things that (1) absorption of light in space has not appreciably affected the results, and (2) the globular clusters are much alike in structure and constitution, differing mainly in distance. (These relative values are based upon apparent diameters, integrated magnitudes, the magnitudes of individual giants or groups of giants, and Cepheid variables; Charlier has obtained much the same results from apparent diameters alone, and Lundmark from apparent diameters and integrated magnitudes.)

Proposition C.—Stars in clusters and in distant parts of the Milky Way are not peculiar—that is, uniformity of conditions and of stellar phenomena naturally prevails throughout the galactic system.

We also share the same opinion, I believe, on the following points:

a. The galactic system is an extremely flattened stellar organization, and the appearance of a Milky Way is partly due to the existence of distinct clouds of stars, and is partly the result of depth along the galactic plane.

b. The spiral nebulae are mostly very distant objects, probably not physical members of our galactic system.

c. If our galaxy approaches the larger order of dimensions, a serious difficulty at once arises for the theory that spirals are galaxies of stars comparable in size with our own: it would be necessary to ascribe impossibly great magnitudes to the new stars that have appeared in the spiral nebulae.

2. Through approximate agreement on the above points, the way is cleared so that the outstanding difference may be clearly stated: Curtis does not believe that the numerical value of the distance I derive for any globular cluster is of the right order of magnitude.

3. The present problem may be narrowly restricted therefore, and may be formulated as follows: Show that any globular cluster

is approximately as distant as derived at Mount Wilson; then the distance of other clusters will be approximately right (see Proposition B), the system of clusters and the galactic system will have dimensions of the order assigned (see Proposition A), and the "comparable galaxy" theory of spirals will have met with a serious, though perhaps not insuperable difficulty.

In other words, to maintain my position it will suffice to show that any one of the bright globular clusters has roughly the distance in light-years given below, rather than a distance one tenth of this value or less:[1]

Cluster	Distance in light-years	Mean photographic magnitude of brightest 25 stars	
		Apparent	Absolute
Messier 13	36,000	13.75	−1.5
Messier 3	45,000	14.23	−1.5
Messier 5	38,000	13.97	−1.4
Omega Centauri	21,000	12.3:	−1.8:

Similarly it should suffice to show that the bright objects in clusters are giants (cf. last column above), rather than stars of solar luminosity.

4. From observation we know that some or all of these four clusters contain:

a. An interval of at least nine magnitudes (apparent and absolute) between the brightest and faintest stars.

b. A range of color-index from −0.5 to +2.0, corresponding to the whole range of color commonly found among assemblages of stars.

c. Stars of types B, A, F, G, K, M (from direct observations of spectra), and that these types are in sufficient agreement with the color classes to permit the use of the latter for ordinary statistical considerations where spectra are not yet known.

d. Cepheid and cluster variables which are certainly analogous to galactic variables of the same types, in spectrum, color change, length of period, amount of light variation, and all characters of the light-curve.

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[1] In the final draft of the following paper Curtis has qualified his acceptance of the foregoing propositions in such a manner that in some numerical details the comparisons given below are no longer accurately applicable to his arguments; I believe, however, that the comparisons do correctly contrast the present view with that generally accepted a few years ago.

e. Irregular, red, small-range variables of the Alpha Orionis type, among the brightest stars of the cluster.

f. Many red and yellow stars of approximately the same magnitude as the blue stars, in obvious agreement with the giant star phenomena of the galactic system, and clearly in disagreement with all we know of color and magnitude relations for dwarf stars.

5. From these preliminary considerations we emphasize two special deductions:

First, a globular cluster is a pretty complete "universe" by itself, with typical and representative stellar phenomena, including several classes of stars that in the solar neighborhood are recognized as giants in luminosity.

Second, we are very fortunately situated for the study of distant clusters—outside rather than inside. Hence we obtain a comprehensive dimensional view, we can determine relative real luminosities in place of relative apparent luminosities, and we have the distinct advantage that the most luminous stars are easily isolated and the most easily studied. None of the brightest stars in a cluster escapes us. If giants or super-giants are there, they are necessarily the stars we study. We cannot deal legitimately with the average brightness of stars in globular clusters, because the faintest limits are apparently far beyond our present telescopic power. Our ordinary photographs record only the most powerful radiators—encompassing a range of but three or four magnitudes at the very top of the scale of absolute luminosity, whereas in the solar domain we have a known extreme range of 20 magnitudes in absolute brightness, and a generally studied interval of twelve magnitudes or more.

6. Let us now examine some of the conditions that would exist in the Hercules Cluster (Messier 13) on the basis of the two opposing values for its distance:

	36,000 light-years	3,600 light-years, or less
a. Mean absolute photographic magnitude of blue stars (C. I. <0.0)	0	$+5$, or fainter
b. Maximum absolute photographic magnitudes of cluster stars	Between -1.0 and -2.0	$+3.2$, or fainter
c. Median absolute photovisual magnitude of long-period Cepheids	-2	$+3$, or fainter
d. Hypothetical annual proper motion	0″.004	0″.04, or greater

a. *The blue stars.*—The colors of stars have long been recognized as characteristic of spectral types and as being of invaluable aid in the study of faint stars for which spectroscopic observations are difficult or impossible. The color-index, as used at Mount Wilson, is the difference between the so-called photographic (pg) and photovisual (pv.) magnitudes—the difference between the brightness of objects in blue-violet and in yellow-green light. For a negative color-index ($\text{C. I.} = \text{pg.} - \text{pv.} < 0.0$) the stars are called blue and the corresponding spectral type is B; for yellow stars, like the sun (type G), the color-index is about +0.8 mag.; for redder stars (types K, M) the color-index exceeds a magnitude.

An early result of the photographic study of Messier 13 at Mount Wilson was the discovery of large numbers of negative color-indices. Similar results were later obtained in other globular and open clusters, and among the stars of the galactic clouds. Naturally these negative color-indices in clusters have been taken without question to indicate B-type stars—a supposition that has later been verified spectroscopically with the Mount Wilson reflectors.[1]

The existence of 15th magnitude B-type stars in the Hercules cluster seems to answer decisively the question of its distance, because B stars in the solar neighborhood are invariably giants (more than a hundred times as bright as the sun, on the average), and such a giant star can appear to be of the fifteenth magnitude only if it is more than 30,000 light-years away.

We have an abundance of material on distances and absolute magnitudes of the hundreds of neighboring B's—there are direct measures of distance, as well as mean distances determined from parallactic motions, from observed luminosity curves, from stream motions, and from radial velocities combined with proper motion. Russell, Plummer, Charlier, Eddington, Kapteyn, and others have worked on these stars with the universal result of finding them giants.

Kapteyn's study of the B stars is one of the classics of modern stellar astronomy; his methods are mainly the well-tried methods generally used for studies of nearby stars. In his various lists of B's more than seventy percent are brighter than zero absolute photographic magnitude,[1] and only two out of 424 are fainter than +3. This result should be compared with the above-mentioned requirement that the absolute magnitudes of the blue stars in Messier 13 should be +5 or fainter in the mean, if the distance of the cluster is 3,600 light-years or less, and no star in the cluster should be brighter than +3.

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[1] **Adams and van Maanen published several years ago the radial velocities and spectral types of a number of B stars in the double cluster in Perseus, *Ast. Jour.*, Albany, N. Y., 27, 1913 (187–188).**

A question might be raised as to the completeness of the material used by Kapteyn and others, for if only the apparently bright stars are studied, the mean absolute magnitudes may be too high. Kapteyn, however, entertains little doubt on this score, and an investigation[2] of the distribution of B-type stars, based on the *Henry Draper Catalogue*, shows that faint B's are not present in the Orion region studied by Kapteyn.

The census in local clusters appears to be practically complete without revealing any B stars as faint as +5. But if the Hercules cluster were not more distant than 3,600 light-years, its B stars would be about as faint as the sun, and the admitted uniformity throughout the galactic system (Proposition C) would be gainsaid: for although near the earth, whether in clusters or not, the B stars are giants, away from the earth in all directions, whether in the Milky Way clouds or in clusters, they would be dwarfs—and the anthropocentric theory could take heart again.

Let us emphasize again that the near and the distant blue stars we are intercomparing are all cluster stars, and that there appears to be no marked break in the gradation of clusters, either in total content or in distance, from Orion through the faint open clusters to Messier 13.

b. *The maximum absolute magnitude of cluster stars.*—In various nearby groups and clusters the maximum absolute photographic brightness, determined from direct measures of parallax or stream motion or from both, is known to *exceed* the following values:

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[1] Stars of types B8 and B9 are customarily treated with the A type in statistical discussion; even if they are included with the B's, 64 per cent of Kapteyn's absolute magnitudes are brighter than zero and only 4 per cent are fainter than +2. No stars of types B8 or B9 fainter than +3 are in Kapteyn's lists.

[2] Shapley, H., *Proceedings Nat. Acad. Sci.*, 5, 1900 (434–440); a further treatment of this problem is to appear in a forthcoming *Mount Wilson Contribution.*

	M
Ursa Major system	−1.0
Moving cluster in Perseus	−0.5
Hyades	+1.0
Scorpio-Centaurus cluster	−2.5
Orion nebula cluster	−2.5
Pleiades	−1.0
61 Cygni group[1]	+1.0

No nearby physical group is known, with the possible exception of the 61 Cygni drift, in which the brightest stars are fainter than +1.0. The mean *M* of the above list of clusters is −0.8; yet for all distant physical groups it must be +3 or fainter (notwithstanding the certain existence within them of Cepheid variables and B-type stars), if the distance of Messier 13 is 3,600 light-years or less. Even if the distance is 8,000 light-years, as Curtis suggests in the following paper, the mean *M* would need to be +1.4 or fainter—a value still irreconcilable with observations on nearby clusters.

The requirement that the bright stars in a globular cluster should be in the maximum only two magnitudes brighter than our sun is equivalent to saying that in Messier 13 there is not one real giant among its thirty or more thousand stars. It is essentially equivalent, in view of Proposition B, to holding that of the two or three million stars in distant clusters (about half a million of these stars have been actually photographed) there is not one giant star brighter than absolute photographic magnitude +2. And we have just seen that direct measures show that all of our nearby clusters contain such giants; indeed some appear to be composed mainly of giants.

As a further test of the distances of globular clusters, a special device has been used with the Hooker reflector. With a thin prism placed in the converging beam shortly before the focus, we may photograph for a star (or for each of a group of stars) a small spectrum that extends not only through the blue region ordinarily photographed, but also throughout the yellow and red. By using specially prepared photographic plates, sensitive in the blue and red but relatively insensitive in the green-yellow, the small spectra are divided in the middle, and the relative intensity of the blue and red parts depends, as is well known, on spectral type and

[1] The absolute visual magnitude of ϵ Virginis (spectrum G6) is 0.0 according to the Mount Wilson spectroscopic parallax kindly communicated by Mr. Adams.

absolute magnitude; giants and dwarfs, of the same type in the Harvard system of spectral classification, show markedly different spectra. The spectral types of forty or fifty of the brighter stars in the Hercules cluster are known, classified as usual on the basis of spectral lines. Using the device described above, a number of these stars have been photographed side by side on the same plate with well known giants and dwarfs of the solar neighborhood for which distances and absolute magnitudes depend on direct measures of parallax. On the basis of the smaller distance for Messier 13, the spectra of these cluster stars (being then of absolute magnitude fainter than +4) should resemble the spectra of the dwarfs. But the plates clearly show that in absolute brightness the cluster stars equal, and in many cases even exceed, the giants—a result to be expected if the distance is of the order of 36,000 light-years.

The above procedure is a variation on the method used by Adams and his associates on brighter stars where sufficient dispersion can be obtained to permit photometric intercomparison of sensitive spectral lines. So far as it has been applied to clusters, the usual spectroscopic method supports the above conclusion that the bright red and yellow stars in clusters are giants.

An argument much insisted upon by Curtis is that the average absolute magnitude of stars around the sun is equal to or fainter than solar brightness, hence, that average stars we see in clusters are also dwarfs. Or, put in a different way, he argues that since the mean spectral class of a globular cluster is of solar type and the average solar-type star near the sun is of solar luminosity, the stars photographed in globular clusters must be of solar luminosity, hence not distant. This deduction, he holds, is in compliance with proposition C—uniformity throughout the universe. But in drawing the conclusions, Curtis apparently ignores, first, the very common existence of red and yellow giant stars in stellar systems, and second, the circumstance mentioned above in Section 5 that in treating a distant external system we naturally first observe its giant stars. If the material is not mutually extensive in the solar domain and in the remote cluster (and it certainly is not for stars of all types), then the comparison of averages means practically nothing because of the obvious and vital selection of brighter stars in the cluster. The comparison should be of nearby cluster with distant cluster, or of the luminosities of the same kinds of stars in the two places.

Suppose that an observer, confined to a small area in a valley, attempts to measure the distances of surrounding mountain peaks. Because of the short base line allowed him, his trigonometric parallaxes are valueless except for the nearby hills. On the remote peaks, however, his telescope shows green foliage. First he assumes approximate botanical uniformity throughout all visible territory. Then he finds that the average height of all plants immediately around him (conifers, palms, asters, clovers, etc.) is one foot. Correlating this average with the measured angular height of plants visible against the sky-line on the distant peaks he obtains values of the distances. If, however, he had compared the foliage on the nearby, trigonometrically-measured hills with that on the remote peaks, or had used some method of distinguishing various floral types, he would not have mistaken pines for asters and obtained erroneous results for the distances of the surrounding mountains. All the principles involved in the botanical parallax of a mountain peak have their analogues in the photometric parallax of a globular cluster.

c. *Cepheid variables.*—Giant stars of another class, the Cepheid variables, have been used extensively in the exploration of globular clusters. After determining the period of a Cepheid, its absolute magnitude is easily found from an observationally derived period-luminosity curve, and the distance of any cluster containing such variables is determined as soon as the apparent magnitudes are measured. Galactic Cepheids and cluster Cepheids are strictly comparable by Proposition C—a deduction that is amply supported by observations at Mount Wilson and Harvard, of color, spectrum, light curves, and the brightness relative to other types of stars.

Curtis bases his strongest objections to the larger galaxy on the use I have made of the Cepheid variables, questioning the sufficiency of the data and the accuracy of the methods involved. But I believe that in the present issue there is little point in laboring over the details for Cepheids, for we are, if we choose, qualitatively quite independent of them in determining the scale of the galactic system, and it is only qualitative results that are now at issue. We could discard the Cepheids altogether, use instead either the red giant stars and spectroscopic methods, or the hundreds of B-type stars upon which the most capable stellar astronomers have worked for years, and derive much the same distance for the Hercules cluster, and for other clusters, and obtain consequently similar dimensions for the galactic system. In fact, the substantiating results from these other sources strongly fortify our belief in the assumptions and methods involved in the use of the Cepheid variables.

Since the distances of clusters as given by Cepheid variables are qualitatively in excellent agreement with the distances as given by blue stars and by yellow and red giants, discussed in the foregoing sub-sections *a* and *b*, I shall here refer only briefly to four points bearing on the Cepheid problem, first noting that if the distances of clusters are to be divided by 10 or 15, the same divisor should be also used for the distances derived for galactic Cepheids.

(1) The average absolute magnitude of typical Cepheids, according to my discussion of proper motions and magnitude correlations, is about -2.5. The material on proper motion has also been discussed independently by Russell, Hertzsprung, Kapteyn, Strömberg, and Seares; they all accept the validity of the method, and agree in making the mean absolute magnitude much the same as that which I derive. Seares finds, moreover, from a discussion of probable errors and of possible systematic errors, that the observed motions are irreconcilable with an absolute brightness five magnitudes fainter, because in that case the mean parallactic motion of the brighter Cepheids would be of the order of $0''.160$ instead of $0''.016 \pm 0''.002$ as observed.

Both trigonometric and spectroscopic parallaxes of galactic Cepheids, as far as they have been determined, support the photometric values in demanding high luminosity; the spectroscopic and photometric methods are not wholly independent, however, since the zero point depends in both cases on parallactic motion.

(2) When parallactic motion is used to infer provisional absolute magnitudes for individual stars (a possible process only when peculiar motions are small and observations very good), the brighter galactic Cepheids indicate the correlation between luminosity and period.[1] The necessity, however, of neglecting individual peculiar motion and errors of observation for this proce-

[1] Mr. Seares has called my attention to an error in plotting the provisional smoothed absolute magnitudes against log period for the Cepheids discussed in *Mount Wilson Contribution* No. 151. The preliminary curve for the galactic Cepheids is steeper than that for the Small Magellanic Cloud, Omega Centauri, and other clusters.

dure makes the correlation appear much less clearly for galactic Cepheids than for those of external systems (where proper motions are not concerned), and little importance could be attached to the period-luminosity curve if it were based on local Cepheids alone. When the additional data mentioned below are also treated in this manner, the correlation is practically obscured for galactic Cepheids, because of the larger observational errors.

On account of the probably universal uniformity of Cepheid phenomena, however, we need to know only the *mean* parallactic motion of the galactic Cepheids to determine the zero point of the curve which is based on external Cepheids; and the *individual* motions do not enter the problem at all, except, as noted above, to indicate provisionally the existence of the period-luminosity relation. It is only this *mean* parallactic motion that other investigators have used to show the exceedingly high luminosity of Cepheids. My adopted absolute magnitudes and distances for all these stars have been based upon the final period-luminosity curve, and not upon individual motions.

(3) Through the kindness of Professor Boss and Mr. Roy of the Dudley Observatory, proper motions have been submitted for 21 Cepheids in addition to the 13 in the *Preliminary General Catalogue*. The new material is of relatively low weight, but the unpublished discussion by Strömberg of that portion referring to the northern stars introduces no material alteration of the earlier result for the mean absolute brightness of Cepheids.

It should be noted that the 18 pseudo-Cepheids discussed by Adams and Joy[1] are without exception extremely bright (absolute magnitudes ranging from −1 to −4); they are thoroughly comparable with the ordinary Cepheids in galactic distribution, spectral characteristics, and motion.

(4) From unpublished results kindly communicated by van Maanen and by Adams, we have the following verification of the great distance and high luminosity of the important, high-velocity, cluster-type Cepheid RR Lyrae:

Photometric parallax	0″.003	(Shapley)
Trigonometric parallax	+0.006±0.006	(van Maanen)
Spectroscopic parallax	0.004	(Adams, Joy, and Burwell)

The large proper motion of this star, 0″.25 annually, led Hertzsprung some years ago to suspect that the star is not distant, and that it and its numerous congeners in clusters are dwarfs. The large proper motion, however, indicates high real velocity rather than nearness, as the above results show. More recently Hertzsprung has reconsidered the problem and, using the cluster variables, has derived a distance of the globular cluster Messier 3 in essential agreement with my value.

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[1] Adams, W. S., and A. H. Joy, *Publ. Ast. Soc. Pac.*, San Francisco, Calif., 31, 1919 (184–186).

d. *Hypothetical annual proper motion.*—The absence of observed proper motion for distant clusters must be an indication of their great distance because of the known high velocities in the line of sight. The average radial velocity of the globular clusters appears to be about 150 km/sec. By assuming, as usual, a random distribution of velocities, the transverse motion of Messier 13 and similar bright globular clusters should be greater than the quite appreciable value of 0."04 a year if the distance is less than 3,600 light-years. No proper motion has been found for distant clusters; Lundmark has looked into this matter particularly for five systems and concludes that the annual proper motion is less than 0."01.

7. Let us summarize a few of the results of accepting the restricted scale of the galactic system.

If the distances of globular clusters must be decreased to one-tenth, the light-emitting power of their stars can be only a hundredth that of local cluster stars of the same spectral and photometric types. As a consequence, I believe Russell's illuminative theory of spectral evolution would have to be largely abandoned, and Eddington's brilliant theory of gaseous giant stars would need to be greatly modified or given up entirely. Now both of these modern theories have their justification, first, in the fundamental nature of their concepts and postulates, and second, in their great success in fitting observational facts.

Similarly, the period-luminosity law of Cepheid variation would be meaningless; Kapteyn's researches on the structure of the local cluster would need new interpretation, because his luminosity laws could be applied locally but not generally; and a very serious loss to astronomy would be that of the generality of spectroscopic methods of determining star distances, for it would mean that identical spectral characteristics indicate stars differing in brightness by 100 to 1, depending only upon whether the star is in the solar neighborhood or in a distant cluster.

THE DIMENSIONS AND ARRANGEMENT OF THE GALACTIC SYSTEM

When we accept the view that the distance of the Hercules cluster is such that its stellar phenomena are harmonious with local stellar phenomena—its brightest stars typical giants, its Cepheids comparable with our own—then it follows that fainter, smaller, globular clusters are still more distant than 36,000 light-years. One-third of those now known are more distant than 100,000 light-years; the most distant is more than 200,000 light-years away, and the diameter of the whole system of globular clusters is about 300,000 light-years.

Since the affiliation of the globular clusters with the galaxy is shown by their concentration to the plane of the Milky Way and their symmetrical arrangement with respect to it, it also follows that the galactic system of stars is as large as this subordinate part. During the past year we have found Cepheid variables and other stars of high luminosity among the fifteenth magnitude stars of the galactic clouds; this can only mean that some parts of the clouds are more distant than the Hercules cluster. There seems to be good reason, therefore, to believe that the star-populated regions of the galactic system extend at least as far as the globular clusters.

One consequence of accepting the theory that clusters outline the form and extent of the galactic system, is that the sun is found to be very distant from the middle of the galaxy. It appears that we are not far from the center of a large local cluster or cloud, but that cloud is at least 50,000 light-years from the galactic center. Twenty years ago Newcomb remarked that the sun *appears* to be in the galactic plane because the Milky Way is a great circle—an encircling band of light—and that the sun also *appears* near the center of the universe because the star density falls off with distance in all directions. But he concludes as follows:

> "Ptolemy showed by evidence, which, from his standpoint, looked as sound as that which we have cited, that the earth was fixed in the center of the universe. May we not be the victim of some fallacy, as he was?"

Our present answer to Newcomb's question is that we have been victimized by restricted methods of measuring distance and by the chance position of the sun near the center of a subordinate system; we have been misled, by the consequent phenomena, into thinking that we are in the midst of things. In much the same way ancient man was misled by the rotation of the earth, with the consequent apparent daily motion of all heavenly bodies around the earth, into believing that even his little planet was the center of the universe, and that his earthly gods created and judged the whole.

If man had reached his present intellectual position in a later geological era, he might not have been led to these vain conceits concerning his position in the physical universe, for the solar system is rapidly receding from the galactic plane, and is moving away from the center of the local cluster. If that motion remains unaltered in direction and amount, in a hundred million years or so the Milky Way will be quite different from an encircling band of star clouds, the local cluster will be a distant object, and the star density will no longer decrease with distance from the sun in all directions.

Another consequence of the conclusion that the galactic system is of the order of 300,000 light-years in greatest diameter, is the previously mentioned difficulty it gives to the "comparable-galaxy" theory of spiral nebulae. I shall not undertake a description and discussion of this debatable problem. Since the theory probably stands or falls with the hypothesis of a small galactic system, there is little point in discussing other material on the subject, especially in view of the recently measured rotations of spiral nebulae which appear fatal to such an interpretation.

It seems to me that the evidence, other than the admittedly critical tests depending on the size of the galaxy, is opposed to the view that the spirals are galaxies of stars comparable with our own. In fact, there appears as yet no reason for modifying the tentative hypothesis that the spirals are not composed of typical stars at all, but are truly nebulous objects. Three very recent results are, I believe, distinctly serious for the theory that spiral nebulae are comparable galaxies—(1) Seares' deduction that none of the known spiral nebulae has a surface brightness as small as that of our galaxy; (2) Reynold's study of the distribution of light and color in typical spirals, from which he concludes they cannot be stellar systems; and (3) van Maanen's recent measures of rotation in the spiral M 33, corroborating his earlier work on Messier 101 and 81, and indicating that these bright spirals cannot reasonably be the excessively distant objects required by the theory.

But even if spirals fail as galactic systems, there may be elsewhere in space stellar systems equal to or greater than ours—as yet unrecognized and possibly quite beyond the power of existing optical devices and present measuring scales. The modern telescope, however, with such accessories as high-power spectroscopes and photographic intensifiers, is destined to extend the inquiries relative to the size of the universe much deeper into space, and contribute further to the problem of other galaxies.

PART II

BY HEBER D. CURTIS

DIMENSIONS AND STRUCTURE OF THE GALAXY

Definition of units employed.—The distance traversed by light in one year, 9.5×10^{12} km., or nearly six trillion miles, known as the light-year, has been in use for about two centuries as a means of visualizing stellar distances, and forms a convenient and easily comprehended unit. Throughout this paper the distances of the stars will be expressed in light-years.

The *absolute* magnitude of a star is frequently needed in order that we may compare the luminosities of different stars in terms of some common unit. It is that *apparent* magnitude which the star would have if viewed from the standard distance of 32.6 light-years (corresponding to a parallax of $0''.1$).

Knowing the parallax, or the distance, of a star, the absolute magnitude may be computed from one of the simple equations:

Abs. Magn. = App. Magn. + 5 + 5 × log (parallax in seconds of arc)

Abs. Magn. = App. Magn. + 7.6 − 5 × log (distance in light-years).

Limitations in studies of galactic dimensions.—By direct methods the distances of individual stars can be determined with considerable accuracy out to a distance of about two hundred light-years.

At a distance of three hundred light-years (28×10^{14} km.) the radius of the earth's orbit (1.5×10^{8} km.) subtends an angle slightly greater than $0''.01$, and the probable error of the best modern photographic parallax determinations has not yet been reduced materially below this value. The spectroscopic method of determining stellar distances through the absolute magnitude probably has, at present, the same limitations as the trigonometric method upon which the spectroscopic method depends for its absolute scale.

A number of indirect methods have been employed which extend our reach into space somewhat farther for the average distances of large groups or classes of stars, but give no information as to the individual distances of the stars of the group or class. Among such methods may be noted as most important the various correlations which have been made between the proper motions of the stars and the parallactic motion due to the speed of our sun in space, or between the proper motions and the radial velocities of the stars.

The limitations of such methods of correlation depend, at present, upon the fact that accurate proper motions are known, in general, for the brighter stars only. A motion of 20 km/sec. across our line of sight will produce the following annual proper motions:

Distance	100 l. y.	500 l. y.	1,000 l. y.
Annual p. m.	0.″14	0.″03	0.″01

The average probable error of the proper motions of Boss is about 0.″006. Such correlation methods are not, moreover, a simple matter of comparison of values, but are rendered difficult and to some extent uncertain by the puzzling complexities brought in by the variation of the space motions of the stars with spectral type, stellar mass (?), stellar luminosity (?), and still imperfectly known factors of community of star drift.

It will then be evident that the base-line available in studies of the more distant regions of our galaxy is woefully short, and that in such studies we must depend largely upon investigations of the distribution and of the frequency of occurrence of stars of the different apparent magnitudes and spectral types, on the assumption that the more distant stars, when taken in large numbers, will average about the same as known nearer stars. This assumption is a reasonable one, though not necessarily correct, as we have little certain knowledge of galactic regions as distant as five hundred light-years.

Were all the stars of approximately the same absolute magnitude, or if this were true even for the stars of any particular type or class, the problem of determining the general order of the dimensions of our galaxy would be comparatively easy.

But the problem is complicated by the fact that, taking the stars of all spectral types together, the dispersion in absolute luminosity is very great. Even with the exclusion of a small number of stars which are exceptionally bright or faint, this dispersion probably reaches ten absolute magnitudes, which would correspond to a hundred-fold uncertainty in distance for a given star. However, it will be seen later that we possess moderately definite information as to the *average* absolute magnitude of the stars of the different spectral types.

Dimensions of our galaxy.—Studies of the distribution of the stars and of the ratio between the numbers of stars of successive apparent magnitudes have led a number of investigators to the postulation of fairly accordant dimensions for the galaxy; a few may be quoted:

Wolf; about 14,000 light-years in diameter.
Eddington; about 15,000 light-years.
Shapley (1915); about 20,000 light-years.
Newcomb; not less than 7,000 light-years; later—perhaps 30,000 light-years in diameter and 5,000 light-years in thickness.
Kapteyn; about 60,000 light-years.[1]

General structure of the galaxy.—From the lines of investigation mentioned above there has been a similar general accord in the deduced results as to the shape and structure of the galaxy:

1. The stars are not infinite in number, nor uniform in distribution.
2. Our galaxy, delimited for us by the projected contours of the Milky Way, contains possibly a billion suns.
3. This galaxy is shaped much like a lens, or a thin watch, the thickness being probably less than one-sixth of the diameter.
4. Our Sun is located fairly close to the center of figure of the galaxy.
5. The stars are not distributed uniformly through the galaxy. A large proportion are probably actually within the ring structure suggested by the appearance of the Milky Way, or are arranged in large and irregular regions of greater star density. The writer believes that the Milky Way is at least as much a structural as a depth effect.

A spiral structure has been suggested for our galaxy; the evidence for such a spiral structure is not very strong, except as it may be supported by the analogy of the spirals as island universes, but such a structure is neither impossible nor improbable. The position of our Sun near the center of figure of the galaxy is not a favorable one for the precise determination of the actual galactic structure.

Relative paucity of galactic genera.—Mere size does not necessarily involve complexity; it is a remarkable fact that in a galaxy of a thousand million objects we observe, not ten thousand different types, but perhaps not more than five main classes, outside the minor phenomena of our own solar system.

1. *The stars.*—The first and most important class is formed by the stars. In accordance with the type of spectrum exhibited, we may divide the stars into some eight or ten main types; even when we include the consecutive internal gradations within these spectral classes it is doubtful whether present methods will permit us to distinguish as many as a hundred separate subdivisions in all. Average space velocities vary from 10 to 30 km/sec., there being a well-marked increase in average space velocity as one proceeds from the blue to the redder stars.

2. *The globular star clusters* are greatly condensed aggregations of from ten thousand

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[1] A complete bibliography of the subject would fill many pages. Accordingly, references to authorities will in general be omitted. An excellent and nearly complete list of references may be found in Lundmark's paper,—"The Relations of the Globular Clusters and Spiral Nebulae to the Stellar System," in *K. Svenska Vet. Handlingar,* Bd. 60, No. 8, p. 71, 1920.

to one hundred thousand stars. Perhaps one hundred are known. Though quite irregular in grouping, they are generally regarded as definitely galactic in distribution. Space velocities are of the order of 300 km/sec.

3. *The diffuse nebulae* are enormous, tenuous, cloud-like masses; fairly numerous; always galactic in distribution. They frequently show a gaseous spectrum, though many agree approximately in spectrum with their involved stars. Space velocities are very low.

4. *The planetary nebulae* are small, round or oval, and almost always with a central star. Fewer than one hundred and fifty are known. They are galactic in distribution; spectrum is gaseous; space velocities are about 80 km/sec.

5. *The spirals.*—Perhaps a million are within reach of large reflectors; the spectrum is generally like that of a star cluster. They are emphatically non-galactic in distribution, grouped about the galactic poles, spiral in form. Space velocities are of the order of 1200 km/sec.

Distribution of celestial genera.—With one, and only one, exception, all known genera of celestial objects show such a distribution with respect to the plane of our Milky Way, that there can be no reasonable doubt that all classes, save this one, are integral members of our galaxy. We see that all the stars, whether typical, binary, variable, or temporary, even the rarer types, show this unmistakable concentration toward the galactic plane. So also for the diffuse and the planetary nebulae and, though somewhat less definitely, for the globular star clusters.

The one exception is formed by the spirals; grouped about the poles of our galaxy, they appear to abhor the regions of greatest star density. They seem clearly a class apart. *Never* found in our Milky Way, there is no other class of celestial objects with their distinctive characteristics of form, distribution, and velocity in space.

The evidence at present available points strongly to the conclusion that the spirals are individual galaxies, or island universes, comparable with our own galaxy in dimensions and in number of component units. While the island universe theory of the spirals is not a vital postulate in a theory of galactic dimensions, nevertheless, because of its indirect bearing on the question, the arguments in favor of the island universe hypothesis will be included with those which touch more directly on the probable dimensions of our own galaxy.

Other theories of galactic dimensions.—From evidence to be referred to later Dr. Shapley has deduced very great distances for the globular star clusters, and holds that our galaxy has a diameter comparable with the distances which he has derived for the clusters, namely,—a galactic diameter of about 300,000 light-years, or at least ten times greater than formerly accepted. The postulates of the two theories may be outlined as follows:

Present Theory	Shapley's Theory
Our galaxy is probably not more than 30,000 light-years in diameter, and perhaps 5,000 light-years in thickness.	The galaxy is approximately 300,000 light-years in diameter, and 30,000, or more, light-years in thickness.
The clusters, and all other types of celestial objects except the spirals, are component parts of our own galactic system.	The globular clusters are remote objects, but a part of our own galaxy. The most distant cluster is placed about 220,000 light-years away.
The spirals are a class apart, and not intra-galactic objects. As island universes, of the same order of size as our galaxy, they are distant from us 500,000 to 10,000,000, or more, light-years.	The spirals are probably of nebulous constitution, and possibly not members of our own galaxy, driven away in some manner from the regions of greatest star density.

EVIDENCE FURNISHED BY THE MAGNITUDE OF THE STARS

The "average" star.—It will be of advantage to consider the two theories of galactic dimensions from the standpoint of the average star. What is the "average" or most frequent type of star of our galaxy or of a globular star cluster, and if we can with some probability postulate such an average star, what bearing will the characteristics of such a star have upon the question of its average distance from us?

No adequate evidence is available that the more distant stars of our galaxy are in any way essentially different from stars of known distance nearer to us. It would seem then that we may safely make such correlations between the nearer and the more distant stars, *en masse*. In such comparisons the limitations of spectral type must be observed as rigidly as possible, and results based upon small numbers of stars must be avoided, if possible.

Many investigations, notably Shapley's studies of the colors of stars in the globular clusters, and Fath's integrated spectra of these objects and of the Milky Way, indicate that the average star of a star cluster or of the Milky Way will, in the great majority of cases, be somewhat like our Sun in spectral type, *i. e.*, such an average star will be, in general, between spectral types F and K.

Characteristics of F–K type stars of known distance.—The distances of stars of type F–K in our own neighborhood have been determined in greater number, perhaps, than for the stars of any other spectral type, so that the average absolute magnitude of stars of this type seems fairly well determined. There is every reason to believe, however, that our selection of stars of these or other types for direct distance determinations has not been a representative one. Our parallax programs have a tendency to select stars either of great luminosity or of great space velocity.

Kapteyn's values for the average absolute magnitudes of the stars of the various spectral types are as follows:

Type	*Average Abs. Magn.*
B5	+1.6
A5	+3.4
F5	+7
G5	,+10
K5	+13
M	+15

The same investigator's most recent luminosity-frequency curve places the maximum of frequency of the stars in general, taking all the spectral types together, at absolute magnitude +7.7.

A recent tabulation of about five hundred modern photographically determined parallaxes places the average absolute magnitude of stars of type F–K at about +4.5.

The average absolute magnitude of five hundred stars of spectral types F to M is close to +4, as determined spectroscopically by Adams.

It seems certain that the two last values of the average absolute magnitude are too low, that is,—indicate too high an average luminosity, due to the omission from our parallax programs of the intrinsically fainter stars. The absolute magnitudes of the dwarf stars are, in general, fairly accurately determined; the absolute magnitudes of many of the giant stars depend upon small and uncertain parallaxes. In view of these facts we may somewhat tentatively take the average absolute magnitude of F–K stars of known distance as not brighter than +6; some investigators would prefer a value of +7 or +8.

Comparison of Milky Way stars with the "average" stars.—We may take, without serious error, the distances of 10,000 and 100,000 light-years respectively, as representing the distance in the two theories from our point in space to the central line of the Milky Way structure. Then the following short table may be prepared:

Apparent magnitudes	Corresponding absolute magnitudes for distances of,—	
	10,000 light-years	100,000 light-years
10	−2.4	−7.4
12	−0.4	−5.4
14	+1.6	−3.4
16	+3.6	−1.4
18	+5.6	+0.6
20	+7.6	+2.6

It will be seen from the above table that the stars of apparent magnitudes 16 to 20, observed in our Milky Way structure in such great numbers, and, from their spectrum, believed ~~to be~~ predominantly F–K in type, are of essentially the same absolute luminosity as known nearer stars of these types, if assumed to be at the average distance of 10,000 light-years. The greater value postulated for the galactic dimensions requires, on the other hand, an enormous proportion of giant stars.

Proportion of giant stars among stars of known distance.—All existing evidence indicates that the proportion of giant stars in a given region of space is very small. As fairly representative of several investigations we may quote Schouten's results, in which he derives an average stellar density of 166,000 stars in a cube 500 light-years on a side, the distribution in absolute magnitude being as follows:

Absolute magnitudes	No. of stars	Relative percentages
−5 to −2	17	.01
−2 to +1	760	.5
+1 to +5	26800	16
+5 to +10	138600	83

Comparison of the stars of the globular clusters with the "average" star.—From a somewhat cursory study of the negatives of ten representative globular clusters I estimate the average apparent visual magnitude of all the stars in these clusters as in the neighborhood of the eighteenth. More powerful instruments may eventually indicate a somewhat fainter mean value, but it does not seem probable that this value is as much as two magnitudes in error. We then have:

Apparent magnitude of average cluster star	Corresponding absolute magnitudes if at distances of,—	
	10 000 light-years	100,000 light-years
18	+5.6	+0.6

Here again we see that the average F–K star of a cluster, if assumed to be at a distance of 10,000 light-years, has an average luminosity about the same as that found for known nearer stars of this type. The greater average distance of 100,000 light-years requires a proportion of giant stars enormously greater than is found in those regions of our galaxy of which we have fairly definite distance data.

While it is not impossible that the clusters are exceptional regions of space and that, with a tremendous spatial concentration of suns, there exists also a unique concentration of giant stars, the hypothesis that cluster stars are, on the whole, like those of known distance seems inherently the more probable.

It would appear, also, that galactic dimensions deduced from correlations between large numbers of what we may term average stars must take precedence over values found from small numbers of exceptional objects, and that, where deductions disagree, we have a right to demand that a theory of galactic dimensions based upon the exceptional object or class shall not fail to give an adequate explanation of the usual object or class.

The evidence for greater galactic dimensions.—The arguments for a much larger diameter for our galaxy than that hitherto held, and the objections which have been raised against the island universe theory of the spirals rest mainly upon the great distances which have been deduced for the globular star clusters.

I am unable to accept the thesis that the globular clusters are at distances of the order of 100,000 light-years, feeling that much more evidence is needed on this point before it will be justifiable to assume that the cluster stars are predominatingly giants rather than average stars. I am also influenced, perhaps unduly, by certain fundamental uncertainties in the data employed. The limitations of space available for the publication of this portion of the discussion unfortunately prevents a full treatment of the evidence. In calling attention to some of the uncertainties in the basal data, I must disclaim any spirit of captious criticism, and take this occasion to express my respect for Dr. Shapley's point of view, and my high appreciation of the extremely valuable work which he has done on the clusters. I am willing to accept correlations between large masses of stellar data, whether of magnitudes, radial velocities, or proper motions, but I feel that the dispersion in stellar characteristics is too large to permit the use of limited amounts of any sort of data, particularly when such data is of the same order as the probable errors of the methods of observation.

The deductions as to the very great distances of the globular clusters rest, in the final analysis, upon three lines of evidence:

1. Determination of the relative distances of the clusters on the assumption that they are objects of the same order of actual size.
2. Determination of the absolute distances of the clusters through correlations between Cepheid variable stars in the clusters and in our galaxy.
3. Determination of the absolute distances of the clusters through a comparison of their brightest stars with the intrinsically brightest stars of our galaxy.

Of these three methods, the second is given most weight by Shapley.

It seems reasonable to assume that the globular clusters are of the same order of actual size, and that from their apparent diameters the *relative* distances may be determined. The writer would not, however, place undue emphasis upon this relation. There would seem to be no good reason why there may not exist among these objects a reasonable amount of difference in actual size, say from three- to five-fold, differences which would not prevent them being regarded as of the same order of size, but which would introduce considerable uncertainty into the estimates of relative distance.

The evidence from the Cepheid variable stars.—This portion of Shapley's theory rests upon the following three hypotheses or lines of evidence:

A. That there is a close coordination between absolute magnitude and length of period for the Cepheid variables of our galaxy, similar to the relation discovered by Miss Leavitt among Cepheids of the Smaller Magellanic Cloud.

B. That, if of identical periods, Cepheids anywhere in the universe have identical absolute magnitudes.

C. This coordination of absolute magnitude and length of period for galactic Cepheids, the derivation of the absolute scale for their distances and the distances of the clusters, and, combined with A) and B), the deductions therefrom as to the much greater dimensions for our galaxy, depend almost entirely upon the sizes and the internal relationships of the proper motions of eleven Cepheid variables.

Under the first heading, it will be seen later that the actual evidence for such a coordination among galactic Cepheids is very weak. Provided that the Smaller Magellanic Cloud is not in some way a unique region of space, the behavior of the Cepheid variables in this Cloud is, through analogy, perhaps the strongest argument for postulating a similar phenomenon among the Cepheid variables of our galaxy.

Unfortunately there is a large dispersion in practically all the characteristics of the stars. That the Cepheids lack a reasonable amount of such dispersion is contrary to all experience for the stars in general. There are many who will regard the assumption made under B) above as a rather drastic one.

If we tabulate the proper motions of these eleven Cepheids, as given by Boss, and their probable errors as well, it will be seen that the average proper motion of these eleven stars is of the order of one second of arc per century in either coordinate; that the average probable error is nearly half this amount, and that the probable errors of half of these twenty-two coordinates may well be described as of the same size as the corresponding proper motions.

Illustrations bearing on the uncertainty of proper motions of the order of 0".01 per year might be multiplied at great length. The fundamental and unavoidable errors in our star positions, the probable errors of meridian observations, the uncertainty in the adopted value of the constant of precession, the uncertainties introduced by the systematic corrections applied to different catalogues, all have comparatively little effect when use is made of proper motions as large as ten seconds of arc per century. Proper motions as small as one second of arc per century are, however, still highly uncertain quantities, entirely aside from the question of the possible existence of systematic errors. As an illustration of the differences in such minute proper motions as derived by various authorities, the proper motions of three of the best determined of this list of eleven Cepheids, as determined by Auwers, are in different quadrants from those derived by Boss.

There seems no good reason why the smaller coordinates of this list of twenty-two may not eventually prove to be different by once or twice their present magnitude, with occasional changes of sign. So small an amount of presumably uncertain data is insufficient to determine the scale of our galaxy, and many will prefer to wait for additional material before accepting such evidence as conclusive.

In view of:

1. The known uncertainties of small proper motions, and,
2. The known magnitude of the purely random motions of the stars, the determination of *individual* parallaxes from *individual* proper motions can never give results of value, though the average distances secured by such methods of correlation from large numbers of stars are apparently trustworthy. The method can not be regarded as a valid one, and this applies whether the proper motions are very small or are of appreciable size.

As far as the galactic Cepheids are concerned, Shapley's curve of coordination between absolute magnitude and length of period, though found through the mean absolute magnitude of the group of eleven, rests in reality upon individual parallaxes determined from individual proper motions, as may be verified by comparing his values for the parallax of these eleven stars with[1] the values found directly from the upsilon component of the proper motion (namely,—that component which is parallel to the Sun's motion) and the solar motion. The differences in the two sets of values, 0''.0002 in the mean, arise from the rather elaborate system of weighting employed.

The final test of a functional relation is the agreement obtained when applied to similar data not originally employed in deducing the relation. We must be ready to allow some measure of deviation in such a test, but when a considerable proportion of other available data fails to agree within a reasonable amount, we shall be justified in withholding our decision.

If the curve of correlation deduced by Shapley for galactic Cepheids is correct in both its absolute and relative scale, and if it is possible to determine individual distances from individual proper motions, the curve of correlation, using the same method as far as the proper motions are concerned (the validity of which I do not admit), should fit fairly well with other available proper motion and parallax data. The directly determined parallaxes are known for five of this group of eleven, and for five other Cepheids. There are, in addition, twenty-six other Cepheids for which proper motions have been determined. One of these was

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[1] *Mt. Wilson Contr.* No 151, Table V.

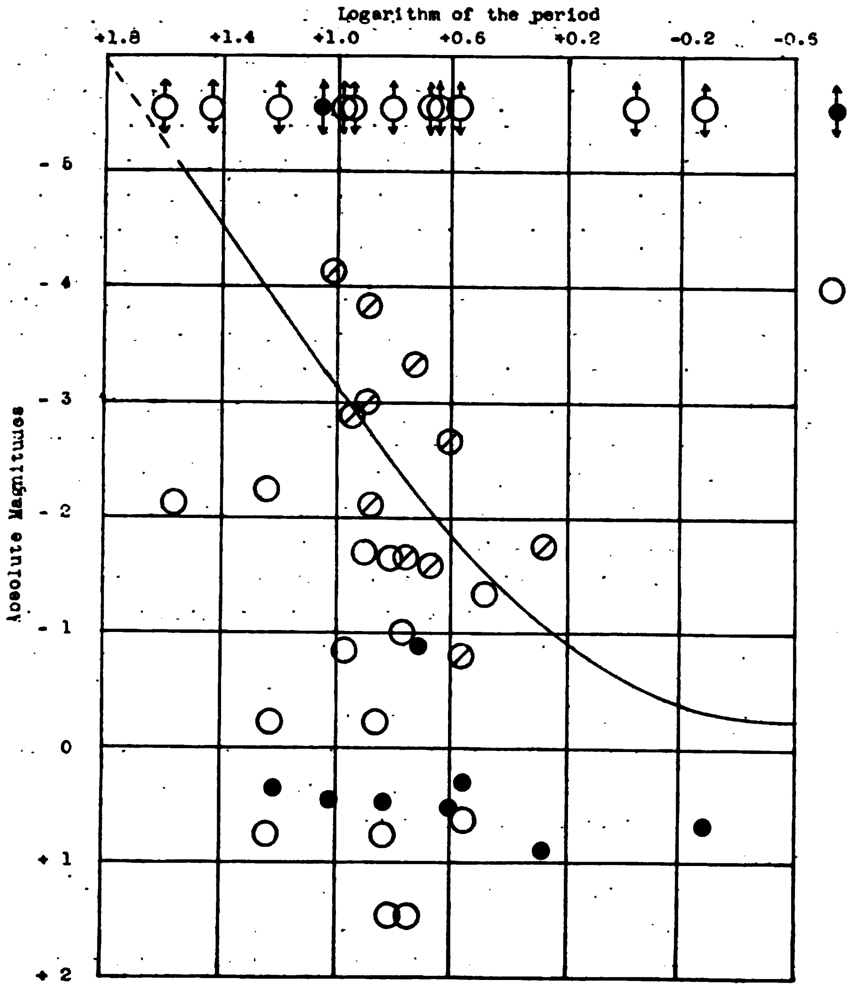

FIG. 1.—Agreement of other data with the luminosity-period correlation curve. Absolute magnitudes calculated from the upsilon component of the proper motion are indicated by circles; the eleven employed by Shapley are marked with a bar. Black dots represent directly determined parallaxes. The arrows attached to the circles at the upper edge of the diagram indicate that either the parallax or the upsilon component of the proper motion is negative, and the absolute magnitude indeterminate in consequence.

omitted by Shapley because of irregularity of period, one for irregularity of the light curve, two because the proper motions were deemed of insufficient accuracy, two because the proper motions are anomalously large; the proper motions of the others have been recently investigated at the Dudley Observatory, but have less weight than those of the eleven Cepheids used by Shapley.

In Figure 1 the absolute magnitudes are plotted against the logarithm of the period; the curve is taken from *Mt. Wilson Contr.* No. 151, and is that finally adopted by Shapley after the introduction of about twelve Cepheids of long period in clusters, twenty-five from the Smaller Magellanic Cloud, and a large number of short period cluster-type variables in clusters with periods less than a day, which have little effect on the general shape of the curve. The barred circles represent the eleven galactic Cepheids employed by Shapley, the black dots those Cepheids for which parallaxes have been determined, while the open circles indicate variables for which proper motions have since become available, or not employed originally by Shapley. For the stars at the upper edge of the diagram, the attached arrows indicate that either the parallax, or the upsilon component of the proper motion is negative, so that the absolute magnitude is indeterminate, and may be anything from infinity-down.

From the above it would seem that available observational data lend little support to the fact of a period-luminosity relation among galactic Cepheids. In view of the large discrepancies shown by other members of the group when plotted on this curve, it would seem wiser to wait for additional evidence as to proper motion, radial velocity, and, if possible, parallax, before entire confidence can be placed in the hypothesis that the Cepheids and cluster-type variables are invariably super-giants in absolute luminosity.

Argument from the intrinsically brightest stars.—If the luminosity-frequency law is the same for the stars of the globular clusters as for our galaxy, it should be possible to correlate the intrinsically brightest stars of both regions and thus determine cluster distances. It would seem, *a priori*, that the brighter stars of the clusters must be giants, or at least approach that type, if the stars of the clusters are like the general run of stars. Through the application of a spectroscopic method Shapley has found that the spectra of the brighter stars in clusters resemble the spectra of galactic giant stars, a method which should be exceedingly useful after sufficient tests have been made to make sure that in this phenomenon, as is unfortunately the case in practically all stellar characteristics, there is not a large dispersion, and also whether slight differences in spectral type may at all materially affect the deductions.

The average "giant" star.—Determining the distance of Messier 3 from the variable stars which it contains, Shapley then derives absolute magnitude −1.5 as the mean luminosity of the twenty-five brightest stars in this cluster. From this mean value, −1.5, he then determines the distances of other clusters. Instead, however, of determining cluster distances of the order of 100,000 light-years by means of correlations on a limited number of Cepheid variables, a small and possibly exceptional class, and from the distances thus derived deducing that the absolute magnitudes of many of the brighter stars in the clusters are as great as −3, while a large proportion are greater than −1, it would seem preferable to begin the line of reasoning with the attributes of known stars in our neighborhood, and to proceed from them to the clusters.

What is the average absolute magnitude of a galactic giant star? On this point there is room for honest difference of opinion, and there will doubtless be many who will regard the conclusions of this paper as ultra conservative. Confining ourselves to existing observational data, there is no evidence that a group of galactic giants, of average spectral type about G5, will have a mean absolute magnitude as great as −1.5; it is more probably in the neighborhood of +1.5, or three absolute magnitudes fainter, making Shapley's distances four times too large.

Russell's suggestion is worth quoting in this connection, written in 1913, when parallax data were far more limited and less reliable than at present:

> The giant stars of all the spectral classes appear to be of about the same mean brightness,—averaging a little above absolute magnitude zero, that is, about a hundred times as bright as the Sun. Since the stars of this series . . . have been selected by apparent brightness, which gives a strong preference to those of greatest luminosity, the average brightness of all the giant stars in a given region of space must be less than this, perhaps considerably so.

Some reference has already been made to the doubtful value of parallaxes of the order of 0″.010, and it is upon such small or negative parallaxes that most of the very great absolute luminosities in present lists depend. It seems clear that parallax work should aim at using as faint comparison stars as possible, and that the corrections applied to reduce relative parallaxes to absolute parallaxes should be increased very considerably over what was thought acceptable ten years ago.

From a study of the plotted absolute magnitudes by spectral type of about five hundred modern direct parallaxes, with due regard to the uncertainties of minute parallaxes, and keeping in mind that most of the giants will be of types F to M, there seems little reason for placing the average absolute magnitude of such giant stars as brighter than +2.

The average absolute magnitude for the giants in Adams's list of five hundred spectroscopic parallaxes is +1.1. The two methods differ most in the stars of type G, where the spectroscopic method shows a maximum at +0.6, which is not very evident in the trigonometric parallaxes.

In such moving star clusters as the Hyades group, we have thus far evidently observed only the giant stars of such groups.

The mean absolute magnitude of forty-four stars believed to belong to the Hyades moving cluster is +2.3. The mean absolute magnitude of the thirteen stars of types F, G, and K, is +2.4 The mean absolute magnitude of the six brightest stars is +0.8 (two A5, one G, and three of K type).

The Pleiades can not fittingly be compared with such clusters or the globular clusters; its composition appears entirely different as the brightest stars average about B5, and only among the faintest stars of the cluster are there any as late as F in type. The parallax of this group is still highly uncertain. With Schouten's value of 0″.037 the mean absolute magnitude of the six brightest stars is +1.6.

With due allowance for the redness of the giants in clusters, Shapley's mean visual magnitude of the twenty-five brightest stars in twenty-eight globular clusters is about 14.5. Then, from the equation given in the first section of this paper we have,—

$$+2 = 14.5 + 7.6 - 5 \times \log \text{distance},$$

or, log distance = 4.02 = 10,500 light-years as the average distance.

If we adopt instead the mean value of Adams +1.1, the distance becomes 17,800 light-years.

Either value for the average distance of the clusters may be regarded as satisfactorily close to those postulated for a galaxy of the smaller dimensions held in this paper, in view of the many uncertainties in the data. Either value, also, will give on the same assumptions a distance of the order of 30,000 light-years for a few of the faintest and apparently most distant clusters. I consider it very doubtful whether any cluster is really so distant as this, but find no difficulty in provisionally accepting it as a possibility, without thereby necessarily extending the main structure of the galaxy to such dimensions. While the clusters seem concentrated toward our galactic plane, their distribution in longitude is a most irregular one, nearly all lying in the quadrant between 270° and 0°. If the spirals are galaxies of stars, their analogy would explain the existence of frequent nodules of condensation (globular clusters?) lying well outside of and distinct from the main structure of a galaxy.

It must be admitted that the B-type stars furnish something of a dilemma in any attempt to utilize them in determining cluster distances.

From the minuteness of their proper motions, most investigators have deduced very great luminosities for such stars in our galaxy. Examining Kapteyn's values for stars of this type, it will be seen that he finds a range in absolute magnitude from +3.25 to −5.47. Dividing the 433 stars of his lists into two magnitude groups, we have:

Mean abs. magn. 249 B stars,
brighter than abs. magn. 0 = −1.32
Mean abs. magn. 184 B stars,
fainter than abs. magn. 0 = +0.99
Mean abs. magn. all = −0.36

Either the value for the brighter stars, −1.32, or the mean of all, −0.36, is over a magnitude brighter than the average absolute magnitude of the giants of the other spectral types among nearer galactic stars.

Now this galactic relation is apparently *reversed* in such clusters as M. 3 or M. 13, where the B-type stars are about three magnitudes fainter than the brighter K and M stars and about a magnitude fainter than those of G type. Supposing that the present very high values for the galactic B-type stars are correct, if we assume similar luminosity for those in the clusters we must assign absolute magnitudes of −3 to −6 to the F to M stars of the clusters, for which we have no certain galactic parallel, with a distance of perhaps 100,000 light-years. On the other hand, if the F to M stars of the cluster are like the brighter stars of these types in the galaxy, the average absolute magnitude of the B-type stars will be only about +3, and too low to agree with present values for galactic B stars. I prefer to accept the latter alternative in this dilemma, and to believe that there may exist B-type stars of only two to five times the brightness of the Sun.

While I hold to a theory of galactic dimensions approximately one-tenth of that supported by Shapley, it does not follow that I maintain this ratio for any particular cluster distance. All that I have tried to do is to show that 10,000 light-years is a reasonable *average* cluster distance.

There are so many assumptions and uncertainties involved that I am most hesitant in attempting to assign a given distance to a given cluster, a hesitancy which is not diminished by a consideration of the following estimates of the distance of M. 13 (The Great Cluster in Hercules).

Shapley, 1915, provisional	100,000 light-years
Charlier, 1916	170 light-years
Shapley, 1917	36,000 light-years
Schouten, 1918	4,300 light-years
Lundmark, 1920	21,700 light-years

It should be stated here that Shapley's earlier estimate was merely a provisional assumption for computational illustration, but all are based on modern material, and illustrate the fact that good evidence may frequently be interpreted in different ways.

My own estimate, based on the general considerations outlined earlier in this paper, would be about 8,000 light-years, and it would appear to me, at present, that this estimate is perhaps within fifty per cent of the truth.

THE SPIRALS AS EXTERNAL GALAXIES

The spirals.—If the spirals are island universes it would seem reasonable and most probable to assign to them dimensions of the same order as our galaxy. If, however, their dimensions are as great as 300,000 light-years, the island universes must be placed at such enormous distances that it would be necessary to assign what seem impossibly great absolute magnitudes to the novae which have appeared in these objects. For this reason the island universe theory has an indirect bearing on the general subject of galactic dimensions, though it is, of course, entirely possible to hold both to the island universe theory and to the belief in the greater dimensions for our galaxy by making the not improbable assumption that our own island universe, by chance, happens to be several fold larger than the average.

Some of the arguments against the island universe theory of the spirals have been cogently put by Shapley, and will be quoted here for reference. It is only fair to state that these earlier statements do not adequately represent Shapley's present point of view, which coincides somewhat more closely with that held by the writer.

> With the plan of the sidereal system here outlined, it appears unlikely that the spiral nebulae can be considered separate galaxies of stars. In addition to the evidence heretofore existing, the following points seem opposed to the "island universe" theory: (a) the dynamical character of the region of avoidance; (b) the size of the galaxy; (c) the maximum luminosity attainable by a star; (d) the increasing commonness of high velocities among other sidereal objects, particularly those outside the region of avoidance . . . the cluster work strongly suggests the hypothesis that spiral nebulae . . . are, however, members of the galactic organization . . . the novae in spirals may be considered as the engulfing of a star by the rapidly moving nebulosity. (*Publ. Astron. Soc. of the Pacific*, Feb. 1918, p. 53.)
>
> The recent work on star clusters, in so far as it throws some light on the probable extent and structure of the galactic system, justifies a brief reconsideration of the question of external galaxies, and apparently leads to the rejection of the hypothesis that spiral nebulae should be interpreted as separate stellar systems.
>
> Let us abandon the comparison with the galaxy and assume an average distance for the brighter spirals that will give a reasonable maximum absolute magnitude for the novae (*and in a footnote;*—provisionally, let us say, of the order of 20,000 light-years). Further, it is possible to explain the peculiar distribution of the spirals and their systematic recession by supposing them repelled in some manner from the galactic system, which appears to move as a whole through a nebular field of indefinite extent. But the possibility of these hypotheses is of course not proposed as competent evidence against the "island universe" theory. . . . Observation and discussion of the radial velocities, internal motions, and distribution of the spiral nebulae, of the real and apparent brightness of novae, of the maximum luminosity of galactic and cluster stars, and finally of the dimensions of our own galactic system, all seem definitely to oppose the "island universe" hypothesis of the spiral nebulae. . . . (*Publ. Astron. Soc. of the Pacific*, Oct. 1919, pp. 261 ff.)

The dilemma of the apparent dimensions of the spirals.—In apparent size the spirals range from a diameter of 2° (Andromeda), to minute flecks 5″, or less, in diameter.

They may possibly vary in actual size, roughly in the progression exhibited by their apparent dimensions.

The general principle of approximate equality of size for celestial objects of the same class seems, however, inherently the more probable, and has been used in numerous modern investigations, *e. g.*, by Shapley in determining the relative distances of the clusters.

On this principle of approximate equality of actual size:

As Island Universes	As Galactic Phenomena
Their probable distances range from about 500,000 light-years (Andromeda), to distances of the order of 100,000,000 light-years. At 500,000 light-years the Nebula of Andromeda would be 17,000 light-years in diameter, or of the same order of size as our galaxy.	If the Nebula of Andromeda is but 20,000 light-years distant, the minute spirals would need to be at distances of the order of 10,000,000 light-years, or far outside the greater dimensions postulated for the galaxy. If all are galactic objects, equality of size must be abandoned, and the minute spirals assumed to be about a thousandfold smaller than the largest.

The spectrum of the spirals.—

As Island Universes	As Galactic Phenomena
The spectrum of the average spiral is indistinguishable from that given by a star cluster. It is approximately F–G in type, and in general character resembles closely the integrated spectrum of our Milky Way. It is just such a spectrum as would be expected from a vast congeries of stars. The spectrum of the spirals offers no difficulties on the island universe theory.	If the spirals are intragalactic, we must assume that they are some sort of finely divided matter, or of gaseous constitution. In either case we have no adequate and actually existing evidence by which we may explain their spectrum. Many diffuse nebulosities of our galaxy show a bright-line gaseous spectrum. Others, associated with bright stars, agree with their involved stars in spectrum, and are well explained as a reflection or resonance effect. Such an explanation seems untenable for most of the spirals.

The distribution of the spirals.—The spirals are found in greatest numbers just where the stars are fewest (at the galactic poles), and not at all where the stars are most numerous (in the galactic plane). This fact makes it difficult, if not impossible, to fit the spirals into any coherent scheme of stellar evolution, either as a point of origin, or as a final evolutionary product. No spiral has as yet been found actually within the structure of the Milky Way.

This peculiar distribution is admittedly difficult to explain on any theory. This factor of distribution in the two theories may be contrasted as follows:

As Island Universes

It is most improbable that our galaxy should, by mere chance, be placed about half way between two great groups of island universes.

So many of the edgewise spirals show peripheral rings of occulting matter that this dark ring may well be the rule rather than the exception.

If our galaxy, itself a spiral on the island universe theory, possesses such a peripheral ring of occulting matter, this would obliterate the distant spirals in our galactic plane, and would explain the peculiar apparent distribution of the spirals.

There is some evidence for such occulting matter in our galaxy.

With regard to the observed excess of velocities of recession, additional observations may remove this. Part of the excess may well be due to the motion of our own galaxy in space. The Nebula of Andromeda is approaching us.

As Galactic Phenomena

If the spirals are galactic objects, they must be a class apart from all other known types: why none in our neighborhood?

Their abhorrence of the regions of greatest star density can only be explained on the hypothesis that they are, in some unknown manner, repelled by the stars.

We know of no force adequate to produce such a repulsion, except perhaps light-pressure.

Why should this repulsion have invariably acted essentially at right angles to our galactic plane?

Why have not some been repelled in the direction of our galactic plane?

The repulsion theory, it is true, is given some support by the fact that most of the spirals observed to date are receding from us.

The space velocities of the spirals.—

As Island Universes

The spirals observed to date have the enormous average space velocity of 1200 km/sec.

In this velocity factor they stand apart from all galactic objects.

Their space velocity is one hundred times that of the galactic diffuse nebulosities, about thirty times the average velocity of the stars, ten times that of the planetary nebulae, and five times that of the clusters.

Such high speeds seem possible for individual galaxies.

Our own galaxy probably has a space velocity, relatively to the system of the spirals, of several hundred km/sec. Attempts have been made to derive this from the velocities of the spirals, but are uncertain as yet, as we have the radial velocities of but thirty spirals.

As Galactic Phenomena

Space velocities of several hundred km/sec. have been found for a few of the fainter stars.

It has been argued that an extension of radial velocity surveys to the fainter stars would possibly remove the discrepancy between the velocities of the stars and those of the spirals.

This is possible, but does not seem probable. The faint stars thus far selected for investigation have been stars of known large proper motions. They are exceptional objects through this method of selection, not representative objects.

High space velocities are the rule, not the exception, for the spirals.

High space velocities are still the exception, not the rule, for the stars of our galaxy.

Proper motions of the spirals.—Should the results of the next quarter-century show *close agreement among different observers* to the effect that the annual motions of translation or rotation of the spirals equal or exceed 0″.01 in average value, it would seem that the island universe theory must be definitely abandoned.

A motion of 700 km/sec. across our line of sight will produce the following annual proper motions:

Distance in light-years	1,000	10,000	100,000	1,000,000
Annual proper motion	″.48	″.048	″.005	″.0005

The older visual observations of the spirals have so large a probable error as to be useless for the determination of proper motions, if small; the available time interval for photographic determinations is less than twenty-five years.

The first proper motion given above should inevitably have been detected by either visual or photographic methods, from which it seems clear that the spirals can not be relatively close to us at the poles of our flattened galactic disk. In view of the hazy character of the condensations measured, I consider the trustworthy determination of the second proper motion given above impossible by present methods without a much longer time interval than is at present available; for the third and the fourth, we should need centuries.

New stars in the spirals.—Within the past few years some twenty-seven new stars have appeared in spirals, sixteen of these in the Nebula of Andromeda, as against about thirty-five which have appeared in our galaxy in the last three centuries. So far as can be judged from such faint objects, the novae in spirals have a life history similar to that of the galactic novae, suddenly flashing out, and more slowly, but still relatively rapidly, sinking again to a luminosity ten thousand-fold less intense. Such novae form a strong argument for the island universe theory and furnish, in addition, a method of determining the approximate distances of the spirals.

With all its elements of simplicity and continuity, our universe is too haphazard in its details to warrant deductions from small numbers of exceptional objects. Where no other correlation is available such deductions must be made with caution, and with a full appreciation of the uncertainties involved.

It seems certain, for instance, that the dispersion of the novae in the spirals, and probably also in our galaxy, may reach at least ten absolute magnitudes, as is evidenced by a comparison of *S Andromedae* with the faint novae found recently in this spiral. A division into two magnitude classes is not impossible.

Tycho's Nova, to be comparable in absolute magnitude with some recent galactic novae, could not have been much more than ten light-years distant. If as close to us as one hundred light-years it must have been of absolute magnitude −8 at maximum; if only one thousand light-years away, it would have been of absolute magnitude −13 at maximum.

The distances and absolute magnitudes of but four galactic novae have been thus far determined; the mean absolute magnitude is −3 at maximum, and +7 at minimum.

These mean values, though admittedly resting upon a very limited amount of data, may be compared with the fainter novae which have appeared in the Nebula of Andromeda somewhat as follows: where 500,000 light-years is assumed for this spiral on the island universe hypothesis and, for comparison, the smaller distance of 20,000 light-years.

	Apparent magnitudes	
	Thirty galactic novae	Sixteen novae in Neb. Andromedae
At maximum	+5	+17
At minimum	+15±	+27 (?; conjectured from the analogy of the galactic novae)

	Absolute magnitudes		
	Four galactic novae of known distance	Sixteen novae in Andr. if at distances of,—	
		500,000 l. y.	20,000 l. y.
At maximum	−3	−4	+3
At minimum	+7	+6?	+13?

It will be seen from the above that, at the greater distance of the island universe theory, the agreement in absolute magnitude is quite good for the galactic and the spiral novae. If as close as 20,000 light-years, however, these novae must be unlike similar galactic objects, and of unusually low absolute magnitude at minimum. Very few stars have thus far been found as low in luminosity as absolute magnitude +13, corresponding, at this distance, to apparent magnitude 27.

The simple hypothesis that the novae in spirals represent the running down of ordinary galactic stars by the rapidly moving nebulosity becomes a possibility on this basis of distance (i. e., 20,000 light-years) for the brighter spirals are within the edges of the galactic system (Shapley).

This hypothesis of the origin of the novae in spirals is open to grave objections. It involves:

1. That the stars thus overtaken are of smaller absolute luminosity than the faintest thus far observed, with very few exceptions.

2. That these faint stars are extraordinarily numerous, a conclusion which is at variance with the results of star counts, which seem to indicate that there is a marked falling off in the number of stars below apparent magnitude 19 or 20.

As an illustration of the difficulties which would attend such a hypothesis, I have made a count of the stars in a number of areas about the Nebula of Andromeda, including, it is believed, stars at least as faint as magnitude 19.5, and find a star density, including all magnitudes, of about 6,000 stars per square degree.

If no more than 20,000 light-years distant this spiral will lie 7,000 light-years from the plane of the Milky Way, and if moving at the rate of 300 km/sec., it will sweep through 385 cubic light-years per year.

To make the case as favorable as possible for the hypothesis suggested, assume that none of the 6,000 stars per square degree are as close as 15,000 light-years, but that all are arranged in a stratum extending 5,000 light-years each way from the spiral.

Then the Nebula of Andromeda should encounter one of these stars every 520 years. Hence the actual rate at which novae have been found in this spiral would indicate a star density about two thousand times as great as that shown by the count; each star would occupy about one square second of arc on the photographic plate.

The spirals as island universes: summary.—

1. On this theory we avoid the almost insuperable difficulties involved in an attempt to fit the spirals in any coherent scheme of stellar evolution, either as a point of origin, or as an evolutionary product.

2. On this theory it is unnecessary to attempt to coordinate the tremendous space velocities of the spirals with those of the average star.

3. The spectrum of the spirals is such as would be expected from a galaxy of stars.

4. A spiral structure has been suggested for our own galaxy, and is not improbable.

5. If island universes, the new stars observed in the spirals seem a natural consequence of their nature as galaxies. Correlations between the novae in the spirals and those in our galaxy indicate distances ranging from perhaps 500,000 light-years in the case of the Nebula of Andromeda, to 10,000,000 or more light-years for the more remote spirals.

6. At such distances, these island universes would be of the same order of size as our own galaxy.

7. Very many spirals show evidence of peripheral rings of occulting matter in their equatorial planes. Such a phenomenon in our galaxy, regarded as a spiral, would serve to obliterate the distant spirals in our galactic plane, and would furnish an adequate explanation of the otherwise inexplicable distribution of the spirals.

There is a unity and an internal agreement in the features of the island universe theory which appeals very strongly to me. The evidence with regard to the dimensions of the galaxy, on both sides, is too uncertain as yet to permit of any dogmatic pronouncements. There are many points of difficulty in either theory of galactic dimensions, and it is doubtless true that many will prefer to suspend judgment until much additional evidence is forthcoming. Until more definite evidence to the contrary is available, however, I feel that the evidence for the smaller and commonly accepted galactic dimensions is still the stronger; and that the postulated diameter of 300,000 light-years must quite certainly be divided by five, and perhaps by ten.

I hold, therefore, to the belief that the galaxy is probably not more than 30,000 light-years in diameter; that the spirals are not intra-galactic objects but island universes, like our own galaxy, and that the spirals, as external galaxies, indicate to us a greater universe into which we may penetrate to distances of ten million to a hundred million light-years.

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COOPERATIVE EXPERIMENTS UPON THE PROTEIN REQUIREMENTS FOR THE GROWTH OF CATTLE

First Report of the Subcommittee on Protein Metabolism in Animal Feeding*

Presented for the Subcommittee by HENRY PRENTISS ARMSBY, Chairman

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SUMMARY

Cooperative experiments on a common plan have been made at three institutions, upon 26 animals in all, in which the effect upon the rate of growth of supplying different amounts of a substantially identical mixture of proteins in the daily rations of calves has been observed.

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*Committee on Food and Nutrition, Division of Biology and Agriculture, National Research Council.

Digestion experiments and determinations of the gain of body protein (metabolism experiments) were carried out on 16 of the animals, the increase in height and girth was determined on 16 and the increase of live weight upon all.

The actual digestibility of the mixed rations proved to be less than that computed by the use of average digestion coefficients for the several constituent feeding stuffs. The difference was in general greater in the low-protein than in the high-protein rations, and greater for the protein than for the total feed (energy).

The accuracy of the determination of the gain of body protein appears to have suffered in some instances from the lack of opportunity to accustom the animals to the necessary experimental conditions.

Because of these irregularities, the results of the experiments, despite careful planning and most conscientious execution, must be considered as indicative rather than demonstrative, pending the results of additional experiments in progress at four other experiment stations. They constitute a reconnaisance rather than a complete survey of the field.

The results here reported seem to indicate that, with this particular protein mixture, a supply in the feed equal to the estimated maintenance requirement plus the normal increase in body protein is at least nearly sufficient to produce a normal gain of body protein and of live weight.

On the other hand, a more liberal supply of protein appears to have distinctly stimulated the rate of gain.

In the computation of rations in practice, using current average figures, it seems that an apparent surplus of 35% of digestible protein above the total of maintenance plus normal gain is sufficient to support a normal rate of growth provided other conditions are favorable, but that a larger allowance may result in a somewhat more rapid growth.

It appears reasonably clear that current feeding standards for growth call for a much greater supply of protein than is necessary to secure satisfactory results.

INTRODUCTION

In June, 1917, at the request of the Agriculture Committee of the National Research Council, the writer undertook to organize cooperative experiments upon some phase of the general question of the protein requirements of farm animals, especially as related to economy of food production during the war. Upon the reorganization of the Research Council in 1919 the Agriculture Committee was merged into the Section of Biology and Agriculture and the further prosecution of the experiments was referred to a subcommittee of the Committee on Food and Nutrition, consisting of Pres. A. F. Woods of the University of Maryland, Dr. E. W. Allen, Director of the Office of Experiment Stations of the U. S. Department of Agriculture, and the writer as chairman.

The Agricultural experiment stations were the natural agencies to undertake such cooperation but the desirability of prompt action forbade any extensive consultation and since a uniform plan was essential to effective cooperation it was thought best to prepare one with the aid of such expert advice as was readily available. Accordingly a project was formulated for the study of the protein requirements for the growth of cattle, this question being one upon which the recorded results and opinions were far from harmonious and moreover one likely to be of economic importance not only during the war but in post-war reconstruction, while it was also of general scientific interest.

With the efficient cooperation of Dr. E. W. Allen this project was submitted to the directors of a selected list of experiment stations which it was believed would be particularly interested and their cooperation was solicited. Accompanying the plan was a letter of explanation from which the following paragraphs are quoted as explanatory of the spirit of the undertaking.

> It is fully recognized that the greatest asset in an undertaking like this is the experience and trained judgment of the individual investigators participating and that these should be allowed the largest possible scope. On the other hand, however, a cooperative undertaking imposes certain unavoidable limitations. The object of cooperation is to secure a large number of results. This necessarily implies comparable experimental methods upon a common plan and a certain sacrifice of individuality.
>
> In the preparation of the plan submitted herewith the endeavor has been to include only such points as appeared essential to effective cooperation. Even this, however, has involved a certain apparent assumption of authority, both as to method of attack and as to experimental details, since no extensive consultation has been practicable. Fortunately, I have been able to avail myself of the advice of some of the leading investigators in this general field and, while accepting full responsibility for the final plan, I desire to acknowledge my especial indebtedness to Dr. C. H. Eckles of the Missouri Experiment Station, Dr. H. S. Grindley of the Illinois Experiment Station, Professor E. B. Hart of the Wisconsin Experiment Station, Professor Lafayette B. Mendel of Yale University, Director F. B. Mumford of the Missouri Experiment Station and Dr. Thomas B. Osborne of the Connecticut Experiment Station.

Considerable interest in the project was expressed but the majority of the stations addressed found it impossible for various reasons to cooperate and up to the present time experiments have been undertaken by only seven stations, viz., those of Maryland, Massachusetts, Nebraska, North Dakota, Pennsylvania, South Dakota, and Virginia and by the Department of Animal Husbandry of the Ohio State University.

Experiments have been made in two successive years on substantially the same plan except that the protein supply of the low protein animals was increased somewhat in the second year. The plan was as follows:

PLAN FOR COOPERATIVE EXPERIMENTS ON PROTEIN REQUIREMENTS FOR THE GROWTH OF CATTLE

Statement of problem.—A productive ration must contain digestible protein at least equal to the maintenance requirement plus the amount of protein contained in the product.

Some recent investigations indicate that at least moderate production may be secured with rations containing but little more digestible protein than the minimum just indicated.

Other investigations, on the contrary, seem to show that a much more liberal protein supply is at least advantageous, if not necessary, and the current feeding standards for growing animals accord with this view.

In most of these investigations little or no attention has been paid to the quality of the proteins consumed, to the influence of accessory substances (vitamines), or to variations in the ash of the rations.

Method of attack.—The general idea is to feed either beef or dairy calves old enough to consume exclusive dry feed upon two different planes of protein intake but with equal net energy supply. The low-protein ration is to supply little more than the minimum amount theoretically required while the high-protein ration is to supply about the amount demanded by current feeding standards. The energy supply is intended to be such as will support normal growth but not cause material fattening.

The proteins of the two rations are to be derived in fixed proportions from identical feeding stuffs and an ample supply of ash ingredients and vitamines is to be assured. Any necessary adjustments in the bulk of the ration are to be made by variations in the amount of straw, and necessary adjustments of the energy supply by the use of greater or smaller amounts of commercial starch.

Animals.—Obviously the animals to be compared must be as nearly alike as possible. The plan contemplates the comparison of the animals by pairs, one animal of each pair receiving the high-protein and one the low-protein ration. The two animals of each pair should be of substantially the same breed (not necessarily full-bloods) and as nearly as possible of the same age and weight at the beginning of the experiment.

It is desired that as many pairs be used as is consistent with the keeping of individual records. Lot records are of far less value. The more nearly alike the several pairs are the better, but uniformity in this respect is not so essential as between the two animals of each pair.

It is desirable to select as young animals as can be expected to eat the proposed rations.

Feed requirements.—Rations are to be computed for different ages to furnish the amounts of digestible true protein and net energy per 1000 pounds live weight shown in the following table, age and not live weight being the controlling factor. The first column shows the theoretical minimum of digestible protein computed in the manner already indicated. It is proposed to increase this by about 35%* in the low-protein ration, in part to compensate for the probable depression of the digestibility, and to make the high-protein ration correspond substantially to Haecker's standards as reported in Henry and Morrison's "Feeds and Feeding," 15th Ed., p. 670. The estimates for net energy are those made by the writer. Figures for intermediate ages can be estimated with sufficient accuracy by interpolation.

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*20% in the first year.

Estimated rations per 1000 lbs. live weight.
(To be computed in direct proportion to the live weight.)

Age	Estimated minimum of digestible protein	Digestible true protein of ration			Net energy
		Low		High	
		1st Year	2nd Year		
Months	Pounds	Pounds	Pounds	Pounds	Therms
4	1.50	1.80	2.03	3.00	18.0
5	1.30	1.56	1.76	2.70	16.1
6	1.20	1.44	1.62	2.40	14.5
9	1.00	1.20	1.35	2.10	12.7
12	0.85	1.00	1.15	2.00	11.8

Feeding stuffs.—It is proposed to supply proteins from a mixture of alfalfa hay, corn meal, linseed meal (O.P.) and high-grade peanut meal, as free from hulls as possible, in such proportions that the digestible true protein of the mixture will be supplied in the following proportions by the several feeding stuffs:

From alfalfa hay	30 per cent
From corn meal	10 per cent
From linseed meal (O.P.)	25 per cent
From peanut meal	33 per cent
	100

It is believed that this will be a well-balanced protein mixture. These particular proportions have been selected because they seem to lend themselves well to the formulation of rations of the desired make-up.

All computations are to be based on the so-called true protein, *i.e.*, crude protein minus non-protein, the non-protein being assumed to be entirely digestible. The factor 6.25 for protein is to be used throughout.

Quality of alfalfa hay.—One important function of the alfalfa hay in the ration is to supply basic ash ingredients and the accessory food substances.

In view of the very considerable variations in the quality of alfalfa hay care should be taken to secure a supply of good quality and especially one containing a normal proportion of leaves since these appear to be the principal carriers of ash and vitamines.

Rations.—To the foregoing mixture of feeding stuffs there is to be added sufficient oat straw and commercial starch to make up rations having the required protein content and energy value per 1000 lbs. Should it seem desirable, sugar may be substituted for part of the starch in amount sufficient to yield the same energy value. Simply as an illustration the following rations have been computed per 1000 pounds live weight for the age of six months on the assumption that the feeding stuffs have the composition and energy values shown in Bulletin No. 142 of the Pennsylvania Station, but using for corn meal the corrected net energy value of 85.20 Therms per 100 pounds reported in the *Journal of Agricultural Research*, v. 10, p. 612 (Sept. 17, 1918). Starch is estimated at 81.79 Therms, and sugar at 81.20 Therms per 100 lbs. dry matter.

High-protein ration	Dry matter	Digestible true protein	Net energy value
	lbs.	lbs.	Therms
10 lbs. Oat straw	8.85	0 08	3.48
10 lbs. Alfalfa hay (all analyses)	9.14	0.70	3.42
3.6 lbs. Corn meal	3.19	0.23	3.07
2.0 lbs. Linseed meal (O. P.)	1.82	0.57	1.78
2.0 lbs. Peanut meal	1.79	0.82	1.87
	24.79	2.40	13.62
1.27 lbs. Starch	1.08	....	0.88
	25.87	2.40	14.50

Low-protein ration*	Dry matter	Digestible true protein	Net energy value
	lbs.	lbs.	Therms
14 lbs. Oat straw	12.39	0.11	4.87
6.34 lbs. Alfalfa hay (all analyses)	5.79	0.45	2.17
2.34 lbs. Corn meal	2.08	0.15	1.99
1.35 lbs. Linseed meal (O. P.)	1.15	0.38	1.18
1.28 lbs. Peanut meal	1.14	0.53	1.20
	22.55	1.62	11.41
4.45 lbs. Starch	3.78	....	3.09
	26.33	1.62	14.50

The actual rations to be used should, however, be computed on the basis of the composition and estimated digestibility of the feeding stuffs actually used and should take account as far as possible of variations in the moisture content of the feeding stuffs.

Feeding.—It is contemplated that the proportions of the several feeding stuffs in the high protein and low protein rations respectively, computed in the manner just illustrated, shall be continued unchanged for the respective animals throughout the experiment. Amounts of these rations sufficient to supply the energy requirements per 1000 pounds live weight given in Table 1 for the different ages will furnish almost exactly the computed amounts of digestible protein required.

It is desirable to adjust the per head ration to the increasing live weight of the animal as frequently as seems practicable. In doing so, allowance should be made for the increase to be expected during the next interval. Thus if the ration is recalculated biweekly the new ration should be based on the live weight at the time of changing plus the increase to be expected during the following week.

*For the second year.

It is quite possible, however, that some modification of this plan may prove necessary. If the proportion of roughage in the rations proves to be too great, the quantity of oat straw may be reduced *for both animals of a pair* by the same amount per 1000 pounds live weight, disregarding the slight change in the protein thus caused or slightly increasing the amount of grain fed in order to keep the protein constant, while the starch is correspondingly decreased so as to keep the energy content unchanged.

It may be necessary also to adjust the energy supply of the animals in order, on the one hand to prevent fattening or on the other to maintain good condition. This may be effected by varying the amount of starch used, but *the energy supply of both animals of a pair must be kept the same per 1000 pounds live weight.*

Measurement of results.—By far the most satisfactory measure of the growth made is the amount of protein stored in the body as shown by the nitrogen balance of the animal. It is therefore urged that, if possible, the income and outgo of nitrogen be determined at intervals. This, of course, requires a quantitative collection of feces and urine and a determination of their nitrogen content. With male animals a separate collection of the two is not particularly difficult. With female animals it is believed that if necessary the two may be collected together and satisfactorily sampled, thus giving data for the nitrogen balance although not for the digestibility.

When a separate collection of the feces is made the data of the ordinary digestion experiment should be determined if practicable. This not only gives a control of the amount of digestible protein actually consumed but aids in estimating the actual energy values of the rations. If the heats of combustion of the feeds and excreta can be determined a still more accurate estimate is possible.

If determinations of the nitrogen balance are not possible, it is believed that useful, even if less accurate, conclusions may be derived from live weight results coupled with careful control of the general condition of the animals. In this case, however, it is especially important to avoid any material fattening, while at the same time maintaining what may be regarded as a good thrifty condition, by an adjustment of the energy supply in the way already indicated. The employment of as many animals as practicable tends to reduce the uncertainties of live weight experiments.

Systematic measurements of a few dimensions suitable for comparing the skeletal growth might aid greatly in the interpretation of the results.

Length of experiment.—It does not seem desirable to stipulate the duration of the experiment nor the frequency with which the digestibility and the nitrogen balance shall be determined. Obviously, the longer the experiment is continued and the more frequent the nitrogen balances or digestion trials, the more information may be hoped for. It is suggested that in the interest of securing results with reasonable promptness a total duration of five or six months may be the most desirable. It may be anticipated that the younger the animals the more decisive will be the results.

Summary.—The most essential requirements for successful cooperation in these experiments may be briefly summarized as follows:

1. Careful selection of animals as regards comparability.
2. All experimenters to use the same protein mixture in as nearly as possible the same relative amounts.
3. The animals to be compared must receive the same relative energy supply at the same age.
4. Growth is to be measured in terms of the nitrogen balance if possible; if not, in terms of live weight and dimensions.

A supplementary control.—If practicable, a useful check upon the results with the low-protein animals would be afforded by adding a third set of animals receiving the same low-protein ration but with skim milk substituted for linseed and peanut meals

as a source of protein, the energy supply being adjusted by varying the amount of starch.
It is not desired, however, that this be undertaken to the detriment of the principal comparison.

Full reports have been prepared of two seasons' work at the Massachusetts and Virginia stations and of one season's at the Ohio State University. With the assent of the investigators at these institutions, this summary and discussion of the results has been prepared by the writer with the understanding that each institution is at liberty to publish as full a report of its own experiments as it may desire. It is hoped to discuss later the results obtained at the other cooperating stations.

RATE OF NORMAL GROWTH

These experiments were not intended to be simply a comparison of wide and narrow nutritive ratios but to be a contribution to our knowledge regarding the minimum amount of protein required to sustain normal growth.

In order to solve this problem, it is obviously necessary to have some standard of normal growth. The simplest and most obvious measure of growth is the increase in size and weight. But even when enough weighings are made to substantially eliminate the considerable fluctuations to which the daily weights of cattle are subject it is still possible that an actual increase of the structural elements of the body maybe, inpart, either masked or exaggerated by a decrease or increase of the amount of body fat.

A method of measuring true growth which is, in principle, more accurate than weighing or measuring the animal consists in determining by means of a balance experiment the amount of nitrogen gained by the animal, since growth is essentially an increase of nitrogenous tissue. If the nitrogen balance can be determined without undue disturbance of the anima, it affords the most accurate measure of the rate of growth at a given date. but, as will appear later, it is not always easy to satisfy this conditionl Both methods were used in these experiments.

Normal increase in weight.—The only extensive study of the normal rate of growth of cattle of which the writer is aware is that of Eckles[1] upon the normal growth of dairy cattle, the observations including the Holstein, Jersey, Ayrshire and Shorthorn breeds and being made upon over sixty animals in all. All the animals were females, while of the twenty-six animals used in the experiments here reported, twenty were males. In the absence, however, of any similar data for bull calves Eckles' averages have been used as a basis for comparison. For ages less than twelve months, as in these experiments, the error involved is probably not great.

Normal gain of protein.—The writer has brought together elsewhere[2] a considerable number of data of more or less value regarding the rate of increase of protein in growth. Haecker's[1] determinations of the composition of the bodies of heavily fed cattle at different ages also afford results in general harmony with the others. With no attempt at the mathematical fitting of a curve to these results, it appears so far as can be judged by inspection alone, that the curve represented by the very simple equation

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[1] *Missouri Experiment Station, Research Bulletin No. 36.*

[2] *U. S. Dept. Agr., Bur. Anim. Indus., Bul. 108* (1908), pp. 13-17: "The nutrition of Farm Animals," 1917, p. 375.

$$g = \frac{135}{a + 20}$$

in which a equals the age in days and g the gain of protein per thousand live weight, gives a very fair fit within the range of age included in these experiments.[2] This equation has been used in succeeding pages as a basis for estimating approximately the normal protein gains of the experimental animals as compared with those actually realized.

INVESTIGATIONS AT THE MASSACHUSETTS AGRICULTURAL EXPERIMENT STATION

By C. L. Beals under the general direction of J. B. Lindsey

EXPERIMENTS OF 1918

ANIMALS

Four pairs of calves were used in the experiments, as shown in Table 1, the experiment extending over 180 days.

PERIODS AND RATIONS

It was not found practicable to start Pair I on the same date as the others but each pair was fed, exclusive of a preliminary period of ten to twenty days, for 180 days sub-divided into six equal periods. The experiment with Pair I began on February 9th and that with other three pairs on January 10th.

The rations for each thirty-day period were computed in proportion to the live weight at the beginning of the period less an allowance of about ten pounds to assure complete consumption of the rations. The rations were intended to correspond with those prescribed in the plan, the computation of the protein and the net energy being based upon the average composition and energy values given in Bulletin 142 of the Pennsylvania Station but with allowance for the varying moisture content of the feeding stuffs as determined by analysis.

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[1] *Proc. Soc. Anim. Prod.*, 1914, p. 18; *Minn. Expt. Sta.*, *Bul. 155*, pp. 6-14, and private communication.

[2] It is obvious, of course, that at early ages it must give much too high values, the computed rate of gain at 20 days before birth being infinite.

TABLE I

Description of animals

Pair	No.	Breed	Sex	Dropped 1917	Age in months at beginning of experiments	High or low protein ration	Initial weight in pounds
I	269	Ayrshire	Bull	Aug. 13	6	High	234
	270	Ayrshire	Bull	Sept. 14	5	Low	202
II	3	Holstein	Heifer	Aug. 1	5½	High	274
	4	Holstein	Heifer	July 24	6	Low	286
III	5	Holstein	Steer	June 1[1]	6	High	260
	6	Holstein	Steer	June 1	6	Low	264
IV	7	Holstein	Steer	June 1[1]	6	High	251
	8	Holstein	Steer	June 1	6	Low	267

DIGESTION AND METABOLISM TRIALS

One digestion and metabolism trial was made with Pair III and two with Pair IV, the excreta being collected for seven days following a 10-day preliminary period. It seems desirable to consider the results of these trials before taking up those upon live weight and size. Full details regarding the feeding are contained in the original report. The average daily rations of the high and low protein lots for the entire 180 days were:

	High protein		Low protein	
	Lbs.	Per cent	Lbs.	Per cent
Oat straw	3.01	37.08	3.86	48.50
Alfalfa Hay	2.88	34.45	1.49	18.72
Corn Meal	1.06	28.47	0.51	32.78
Linseed Meal	0.58		0.29	
Peanut Meal	0.52		0.27	
Starch	0.22		1.54	
	8.27	100.00	7.96	100.00

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[1] Approximate date.

Digestibility.—The following tables show the dates of the several digestion experiments, the weights of the nutrients digested and the percentage digestibility. As appears from the dates given, the digestion experiments fell in the sixth thirty-day period in the case of Pair III and in the fifth and sixth thirty-day periods for Pair IV. In these trials, the straw, hay and mixed grain (inclusive of the starch), but not the single grains, were analyzed except that the non-protein was not determined. The digestibility of the true protein has been computed by the writer on the assumption that the percentages of non-protein were the same as those shown in the table on p. 17 of Pennsylvania Bulletin No. 142 and that it was completely digested.

As appears from Table 2, the percentage digestibility of the protein was, as was to be expected, considerably lower in the low-protein than in high-protein rations while the digestibility of the crude fiber was also lower in two out of three cases. The digestibility of the nitrogen-free extract, on the other hand, tends to be somewhat higher in the low than in the high protein rations, owing doubtless to the considerable amount of starch which the former contained. This, however, is offset by the lower digestibility of the crude fiber, so that the digestibility of the total crude fiber + nitrogen-free extract shows an extreme range of only 2.6 in the case of Pair IV and of only 3.3 in the case of Pair III. In two cases out of the three the percentage digestibility of the total dry matter was less in the low-protein than in the high-protein ration by about 3.5 while in the third case the two were substantially equal.

On the other hand, however, the observed digestibility of the dry matter and protein of the mixed rations was distinctly lower than that computed from the actual composition of the feeding stuffs by the use of average digestion coefficients. From the data reported by the authors, using the coefficients given by Henry and Morrison[1] in their Table II, the results in Table 3 have been computed by the writer. In making these computations the digestibility of the crude protein of the grain mixture has been taken as the weighted mean of the coefficients for its several ingredients.

In the high protein rations the deficit in digestibility as compared with that computed is not very large, ranging from 5.4 to

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[1] "Feeds and Feeding," 15th Ed., page 647.

TABLE 2

Amount digested per day and head

	Weights digested		Percentage digestibility	
	High-protein Grams	Low-protein Grams	High-protein Per cent	Low-protein Per cent
Pair III	No. 5.	No. 6.	No. 5.	No. 6.
June 19-25				
Dry matter	2273.8	2027.1	58.45	54.90
Ash	101.0	106.1	29.13	35.83
Crude protein	380.2	179.5	68.59	57.15
True protein[1]	318.1	149.9	64.64	52.69
Crude fiber	503.5	330.5	51.06	37.16
Nitrogen-free extract	1189.5	1352.4	64.44	64.71
Ether extract	99.6	58.6	63.45	56.83
Fiber + N-fr. extract	1693.0	1682.9	59.76	56.49
Pair IV	No. 7.	No. 8.	No. 7.	No. 8.
June 5-11				
Dry matter	2067.9	2169.0	57.14	57.70
Ash	90.7	98.9	30.43	32.71
Crude protein	359.0	203.3	68.93	58.10
True protein[1]	301.1	172.2	65.04	54.02
Crude fiber	525.5	484.5	51.99	48.84
Nitrogen-free extract	1007.0	1323.7	61.24	65.98
Ether extract	85.7	58.6	59.05	54.09
Fiber + N fr. extract	1532.5	1808.2	57.72	60.31
June 27-July 3				
Dry matter	2244.5	2141.2	58.84	55.24
Ash	112.8	82.0	36.20	27.24
Crude protein	375.3	164.3	69.47	51.33
True protein[1]	314.6	133.2	65.61	46.09
Crude fiber	419.8	451.0	39.71	43.59
Nitrogen-free extract	1234.9	1387.0	70.39	65.60
Ether extract	101.7	56.9	67.20	53.67
Fiber + N-fr. extract	1654.7	1838.0	58.85	58.37

7.0 for the dry matter and from 3.4 to 4.5 for the crude protein. In the low protein rations it is more considerable, ranging from 8.8 to 11.6 for the dry matter and from 6.7 to 14.9 for the crude protein.

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[1] Computed by the writer.

TABLE 3

Observed and computed digestibility of dry matter and crude protein

	Dry matter		Crude protein	
	Observed Per cent	Computed Per cent	Observed Per cent	Computed Per cent
Pair III				
June 19-25				
No. 5, High Protein	58.45	64.1	68.59	73.1
No. 6, Low Protein	54.90	66.5	57.15	65.3
Pair IV				
June 5-11				
No. 7, High Protein	57.14	64.1	68.93	72.3
No. 8, Low Protein	57.70	66.5	58.10	64.8
June 27-July 3				
No. 7, High Protein	58.84	64.2	69.47	73.6
No. 8, Low Protein	55.24	66.5	51.33	66.2

Intended and actual feed supply.—As already stated, the rations for each successive thirty days were intended to supply the amounts of digestible protein and net energy called for by the plan of the experiments. Due, however, to the relatively low digestibility of the rations just noted, and also because the amounts of feed actually consumed per 1000 pounds live weight were slightly less than was expected, the actual amounts of both protein and energy supplied in the digestion trials were less than intended, the energy deficit being greater in the low-protein than in the high-protein rations, except in the case of Calves 7 and 8 in the first digestion trial, while the protein deficit was about the same.

Actual results on this point are available only in the digestion trials. The results of the latter cannot well be applied to the remainder of the experiment for the reason that the proportions of the different feeding stuffs varied more or less, but it may be regarded as probable that they show a similar discrepancy.

From the data of Table 2 and the average live weights for the first two and last two days of each digestion trial, the digestible true protein and net energy of the rations consumed per 1000 pounds live weight at the time of the digestion trials have been computed and compared with the amounts intended, with the results shown in Table 4. In this table the amounts of protein are computed from those per head shown in Table 2 while the net energy has been computed by the writer, in substantially the manner elsewhere[1] described by him, from the total dry matter and the digestible organic matter of the total rations, using the following estimated factors:

Metabolizable energy per gram digestible organic matter	3.7 Cals.[2]
Heat increment per gram of total dry matter	1.15 Cals.

TABLE 4

Protein and energy supply per 1000 pounds live weight in digestion trials

	Pair IV June 5-11		Pair III June 19-25		Pair IV June 27-July 3	
	Digestible true protein Lbs.	Net energy Therms	Digestible true protein Lbs.	Net energy Therms	Digestible true protein Lbs.	Net energy Therms
High protein rations						
Calf No. 5						
Intended			2.00	11.80		
Actual			1.74	8.84		
Calf No. 7						
Intended	2.03	12.10			2.00	11.80
Actual	1.80	8.53			1.73	8.72
Low protein rations						
Calf No. 6						
Intended			1.00	11.80		
Actual			0.84	7.26		
Calf No. 8						
Intended	1.07	12.10			1.00	11.80
Actual	0.98	8.62			0.70	7.52

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[1] "The Nutrition of Farm Animals," p. 674.

[2] Computed from Table 191, p. 649, of "The Nutrition of Farm Animals," assuming an average of 70% roughage and 30% grain in the rations. The result (3.7) agrees with figures of Table 192 of the same book.

The intended amounts of digestible protein and net energy in the foregoing table are those computed by the authors upon the live weights at the beginning of each trial by applying the data of Bulletin 142 of The Pennsylvania Station to the feeding stuffs used. They correspond, therefore, to the rations contemplated in the plan. Substantially the same results as regards net energy are also afforded by a computation like that made by the writer but based on the estimated instead of the actual digestible matter of the rations.

Gains of protein.—In these investigations the digestion trials included also the quantitative collection of the urine and the determination of the nitrogen balance. The corresponding daily gains of protein (N × 6.0) per head and per 1000 pounds average live weight during each digestion trial are shown in Table 5. From these data it appears that the animal of each pair which received the high protein ration made a distinctly greater gain of protein than did its mate receiving the low protein ration. No corresponding data are available, of course, for the remainder of the experiments nor for the other animals.

TABLE 5

Daily gains of protein

	Pair IV June 5-11	Pair III June 19-25	Pair IV June 27-July 3
High protein			
Calf No. 5			
Per head		103.92 gm.	
Per 1000 lbs. live weight		0.57 lb.	
Calf No. 7			
Per head	58.68 gm.		86.64 gm
Per 1000 lbs. live weight	0.35 lb.		0.48 lb.
Low protein			
Calf No. 6			
Per head		72.72 gm.	
Per 1000 lbs. live weight		0.41 lb.	
Calf No. 8*			
Per head	51.48 gm.		48.72 gm.
Per 1000 lbs. live weight	0.29 lb.		0.26 lb.

*The results for Calf No. 8 include an estimated correction for urine lost equivalent to 8.10 grams protein per head in the first trial and 1.04 grams in the second trial.

Before drawing conclusions as to the protein requirements of these animals, however, it must be considered that, owing to the relatively low digestibility as compared with that reckoned upon, all the animals, but particularly those on the low protein rations, consumed less energy than was contemplated. It appears desirable also to make such comparisons as are possible with the normal rate of increase of body protein at the several ages as estimated in the manner described in the introduction (p. 227).

TABLE 6

Protein supply and daily gains per 1000 pounds live weight

	Pair IV June 5-11 Age 372 days	Pair III June 19-25 Age 386 days	Pair IV June 27-July 3 Age 394 days
High protein	lbs.	lbs.	lbs.
Calf No. 5			
Digestible protein consumed		1.74	
Estimated maintenance requirement		0.50	
Available for growth		1.24	
Observed gain of protein		0.57	
Estimated normal gain		0.33	
Calf No. 7			
Digestible protein consumed	1.80		1.73
Estimated maintenance requirement	0.50		0.50
Available for growth	1.30		1.23
Observed gain of protein	0.35		0.48
Estimated normal gain	0.34		0.33
Low protein			
Calf No. 6			
Digestible protein consumed		0.84	
Estimated maintenance requirement		0.50	
Available for growth		0.34	
Observed gain of protein		0.41	
Estimated normal gain		0.33	
Calf No. 8			
Digestible protein consumed	0.98		0.70
Estimated maintenance requirement	0.50		0.50
Available for growth	0.48		0.20
Observed gain of protein	0.29		0.26
Estimated normal gain	0.34		0.33

In Table 6 the ages of the animals at the middle of the several digestion trials and the corresponding estimated normal gains of protein are compared with the actual gains of protein shown in Table 5, with the amounts of digestible protein in the rations (Table 4), and with the quantities available for growth after the estimated maintenance requirement was met, the latter being estimated at 0.50 lb. per 1000 pounds live weight (compare p. 276). In the case of Pair III, the calf receiving the low-protein ration (No. 6), which actually received only the minimum of protein estimated in the plan as necessary, appears from Table 6 to have made somewhat more than the normal gain of protein. His mate (No. 5), which received twice as much digestible protein, made a still greater gain of protein, some of which at least may be plausibly ascribed to the greater amount of net energy in his ration as computed in Table 4.

In the case of Pair IV, in the first digestion trial the animal receiving the low-protein ration (No. 8) received but slightly less digestible protein than was intended but made a gain distinctly below the estimated normal. Its mate, on the high-protein ration, with practically the same amount of net energy, made almost exactly the estimated normal gain. In the second digestion trial with the same pair, the low-protein animal (No. 8) received an amount of digestible protein decidedly below the estimated minimum, while the amount of net energy was also low. His gain fell materially below the normal while the high-protein animal of the pair, with much more net energy, made a gain considerably in excess of the normal.

Of course too much stress must not be laid on differences of a few hundredths of a pound of protein gained, yet on the whole the testimony of the nitrogen balances seems to indicate that the protein supply of the low-protein animals was scarcely sufficient to permit full utilization of their powers of growth but it at least suggests that a comparatively small increase of protein would have sufficed to do so.

It must be remembered, however, that, as shown in Table 4, the supply of net energy was much below that estimated to be required for normal growth and that this deficit is greater in the low-protein rations, averaging 35% as against 26% in the high protein rations. This deficiency may very well have tended to increase the rate of protein katabolism and thus to cut down the rate of gain. On the other hand, however, the live weight results to be considered immediately hardly seem to indicate any great deficiency of net energy in the experiments as a whole.

INCREASE IN WEIGHT AND SIZE

Live weight.—The live weight of each animal was taken on two consecutive days at the beginning of the experiment and at the close of each 15 days. The increases per head in each successive interval and the cumulated increases are recorded in Table 7. Considerable fluctuation in the increase in successive intervals is to be noted, probably due in part to the weights being the average of only two weighings. The total gain by the high protein animal of each pair was greater than that of its mate on the low protein ration, both absolutely and in comparison with the initial live weight. Of the animals on which digestion trials were made,

TABLE 7

Gains in live weight

At end of	Pair I				Pair II			
	No. 269 High protein		No. 270 Low protein		No. 3 High protein		No. 4 Low protein	
	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
First 15 days	16.0	16.0	13.5	13.5	17.5	17.5	14.0	14.0
Second 15 days	11.0	27.0	10.0	23.5	16.0	33.5	7.0	21.0
Third 15 days	13.0	40.0	6.0	29.5	18.5	52.0	25.0	46.0
Fourth 15 days	17.0	57.0	12.5	42.0	19.0	71.0	8.0	54.0
Fifth 15 days	6.5	63.5	9.0	51.0	6.0	77.0	17.5	71.5
Sixth 15 days	7.5	71.0	11.5	62.5	19.5	96.5	4.0	75.5
Seventh 15 days	11.0	82.0	6.0	68.5	23.0	119.5	10.5	86.0
Eighth 15 days	31.5	113.5	16.0	84.5	−2.5	117.0	19.0	105.0
Ninth 15 days	22.5	136.0	17.5	102.0	14.0	131.0	3.0	108.0
Tenth 15 days	12.5	148.5	7.5	109.5	26.0	157.0	23.5	131.5
Eleventh 15 days	20.0	168.5	11.5	121.0	26.5	183.5	25.0	156.5
Twelfth 15 days	7.5	176.0	15.0	136.0	11.0	194.5	17.5	174.0

TABLE 7—(*Continued*)

	Pair III				Pair IV			
	No. 5 High protein		No. 6 Low protein		No. 7 High protein		No. 8 Low protein	
At end of	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
First 15 days	15.0	15.0	9.0	9.0	15.5	15.5	3.0	3.0
Second 15 days	0.0	15.0	6.5	15.5	4.5	20.0	14.0	17.0
Third 15 days	28.0	43.0	18.0	33.5	24.5	44.5	20.0	37.0
Fourth 15 days	19.0	62.0	22.0	55.5	10.0	54.5	6.5	43.5
Fifth 15 days	13.0	75.0	5.0	60.5	17.5	72.0	30.5	74.0
Sixth 15 days	18.5	93.5	14.0	74.5	11.0	83.0	9.0	83.0
Seventh 15 days	19.0	112.5	16.0	90.5	6.5	89.5	15.5	98.5
Eighth 15 days	5.0	117.5	–2.5	88.0	15.0	104.5	0.0	98.5
Ninth 15 days	–1.0	116.5	20.0	108.0	23.0	127.5	33.5	132.0
Tenth 15 days	28.5	145.0	25.0	133.0	12.0	139.5	5.5	137.5
Eleventh 15 days	13.0	158.0	13.5	146.5	18.5	158.0	22.0	159.5
Twelfth 15 days	23.5	181.5	15.0	161.5	29.0	187.0	16.5	176.0

No. 6 of Pair III, on the low protein ration, consumed rather less net energy than did its mate, No. 5, on the high protein ration, as appears from Table 4, this suggesting that the relatively lower gain in weight may be due in part to deficiency of energy. The same may also be said of No. 8 as compared with No. 7 (Pair IV) in the second digestion trial, but not in the first. The average gains per head by the two groups during the entire 180 days were as follows:

	Total	Per day	Percentage of initial live weight
	Lbs.	Lbs.	
High protein	184.75	1.03	72.5
Low protein	161.88	0.90	62.5

A comparison of the live weights of the calves with Eckles' growth curves of Holstein and Ayrshire heifers (page 226) is shown in Figure 1. It is apparent that these animals were lighter than those of the corresponding breeds observed by Eckles but that the rate of increase of the two Ayrshires was about the same while that of the six Holsteins was slightly less.

Height and girth.—The height and girth of each animal was measured at the times of weighing. The results as to increase in size correspond substantially with those on live weight, except that No. 6 on the low protein ration made a notably greater increase in height than did its mate, No. 5, on the high protein

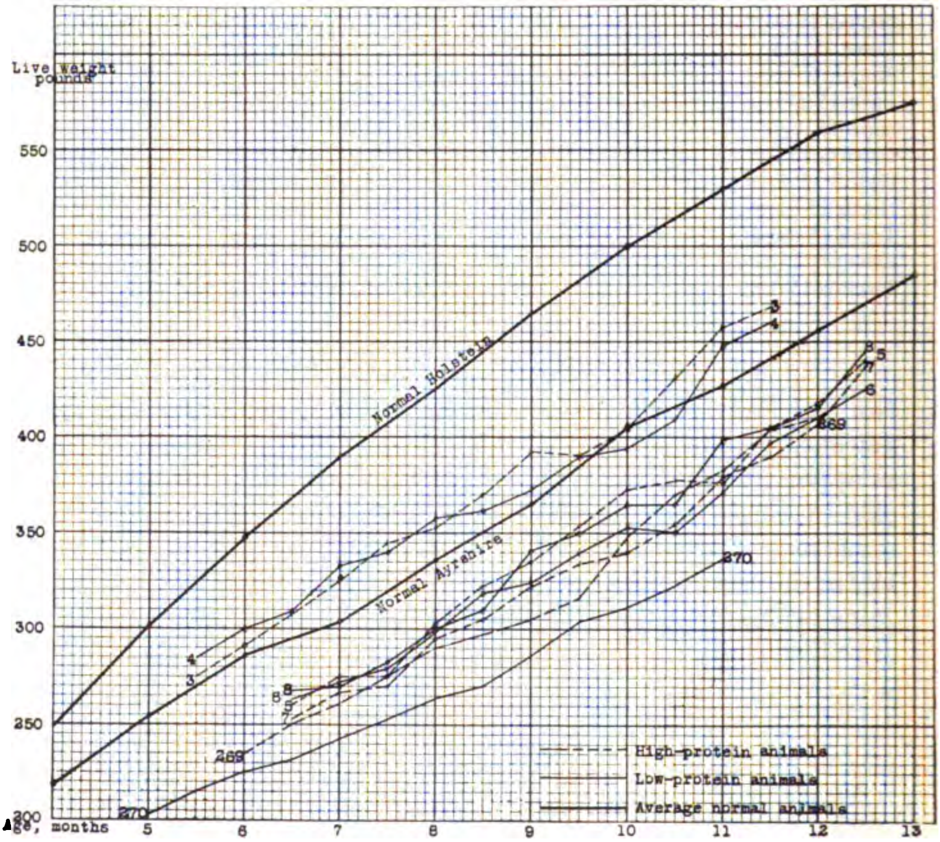

FIG. 1—Live weights of animals. Experiments conducted at the Massachusetts station in 1918. The numbers appearing at the ends of each curve in this figure refer to animals as numbered in Table 7.

ration, while, on the other hand, these two animals made almost identical increase of girth. The results regarding total increase for each animal and the means for the two groups are shown in Table 8.

TABLE 8

Total increase in height and girth

		Height in inches	Girth in inches
Pair I	No. 269 High protein	4.94	7.25
	No. 270 Low protein	4.00	6.13
Pair II	No. 3 High protein	6.81	8.63
	No. 4 Low protein	5.75	7.88
Pair III	No. 5 High protein	5.50	7.38
	No. 6 Low protein	6.31	7.25
Pair IV	No. 7 High protein	6.63	7.13
	No. 8 Low protein	6.63	7.13
Means	High protein	5.97	7.60
	Low pro'ein	5.67	7.10

It would seem that the results upon increase in live weight and size confirm the conclusions drawn on page 235 from the nitrogen balances, namely, that the protein supply of the low protein animals was probably slightly below the minimum required for normal growth, while, as there stated, they do not indicate any material deficiency in the energy supply.

INVESTIGATIONS AT THE MASSACHUSETTS EXPERIMENT STATION (CONTINUED)

EXPERIMENTS OF 1919

The general plan for the experiments of 1919 was the same as in the previous year except that the protein supply of the low protein group, as explained on page 222, was to be increased 35% above the estimated minimum requirement instead of 20%.

ANIMALS

As in 1918, four pairs of calves were fed for 180 days upon the prescribed rations. The description of the animals is contained in Table 9.

TABLE 9

Description of animals

Pair	No.	Breed	Sex	Dropped 1918	Age in months at beginning of experiments	High or low protein ration	Initial weight in lbs.
I	19	Holstein	Heifer	Aug. 26	4	High	214.0
	18	Holstein	Heifer	July 31	5	Low	302.5
II	21	Holstein	Steer	Aug. 29	4	High	284.0
	20	Holstein	Steer	Aug. 20	4½	Low	288.5
III	23	Holstein	Steer	July 1	6	High	300.0
	22	Holstein	Steer	July 1	6	Low	292.5
IV	25	Holstein	Heifer	May 21	7½	High	326.5
	24	Holstein	Heifer	May 21	7½	Low	300.0

PERIODS AND RATIONS

After a preliminary period of 15 days, the experiment proper was begun on January 1, 1919, with all the animals, being divided into 12 periods of 15 days each.

The rations were computed to correspond with those prescribed in the plan as in 1918 except that the recalculations to allow for increased age and weight were made every 15 days instead of every 30 days. Full details of the daily rations are contained in the original report. The daily average rations per head for the entire 180 days were:

	High-protein Pounds	Low-protein Pounds
Oat straw	3.00	4.47
Alfalfa hay	3.16	3.05
Corn meal	1.20	0.81
Linseed meal	0.67	0.42
Peanut meal	0.62	0.39
Starch	0.37	1.67

DIGESTION AND METABOLISM EXPERIMENTS

Digestion and metabolism experiments were made with the animals of Pairs II and III in the even-numbered 15-day periods, viz., with Pair II (Nos. 20 and 21) in the 2d, 6th and 10th periods,

TABLE 10

Amount digested per day and head

	Weights digested		Percentage digestibility	
	No. 21 High-protein	No. 20 Low-protein	No. 21 High-protein	No. 20 Low-protein
	Grams	Grams	Per cent	Per cent
Pair II				
Period II				
January 25-31, incl.				
Dry matter	2154.95	2140.09	65.58	65.31
Ash	84.28	78.88	42.02	37.43
Crude protein	376.07	247.90	72.06	64.35
True protein	313.64	206.41	68.27	60.06
Crude fiber	358.37	365.01	47.87	49.06
Nitrogen-free extract	1263.28	1398.75	74.17	75.54
Ether extract	72.94	49.54	65.48	57.96
Fiber+N -fr. extract	1621.65	1763.76	66.13	67.96
Period VI				
March 26-April 1, incl.				
Dry matter	1951.40	2302.74	51.67	58.88
Ash	18.10	74.27	6.84	27.48
Crude protein	367.90	229.53	63.65	55.92
True protein	301.11	184.48	58.90	50.49
Crude fiber	272.67	385.70	31.34	42.55
Nitrogen-free extract	1217.95	1557.03	63.48	70.63
Ether extract	74.77	56.20	51.48	47.20
Fiber+N -fr. extract	1490.62	1942.73	53.45	62.44
Period X				
May 25-31, incl.				
Dry matter	2577.04	2511.28	60.32	57.08
Ash	156.73	79.64	45.09	25.24
Crude protein	485.25	270.88	72.28	57.64
True protein	412.91	224.64	68.94	53.02
Crude fiber	448.33	448.90	44.84	42.49
Nitrogen-free extract	1365.51	1629.65	65.73	67.44
Ether extract	122.23	82.22	69.13	58.18
Fiber+N -fr. extract	1813.84	2078.55	58.94	59.85

TABLE 10—(*Continued*)

	Weights digested		Percentage digestibility	
	No. 23 High-protein	No. 22 Low-protein	No. 23 High-protein	No. 22 Low-protein
	Grams	Grams	Per cent	Per cent
Pair III				
Period IV				
February 22-28, incl.				
Dry matter	2286.78	2208.03	62.16	63.17
Ash	82.80	59.41	33.46	24.60
Crude protein	359.56	196.53	68.68	58.14
True protein	294.66	156.22	64.24	52.47
Crude fiber	448.29	442.51	49.00	51.96
Nitrogen-free extract	1308.10	1449.01	70.57	74.01
Ether extract	88.03	60.55	63.21	56.71
Fiber + N.- fr. extract	1756.39	1891.52	63.44	67.33
Period VIII				
April 25-May 1, incl.				
Dry matter	2640.18	2401.36	61.78	61.53
Ash	100.45	71.47	38.38	32.67
Crude protein	443.52	252.34	71.62	59.59
True protein	369.94	207.83	67.79	54.72
Crude fiber	580.85	543.64	51.23	52.95
Nitrogen-free extract	1402.01	1480.88	66.91	69.64
Ether extract	113.36	62.73	68.17	53.65
Fiber + N.-fr. extract	1982.86	2024.52	61.40	64.21
Period XII				
June 24-30, incl.				
Dry matter	2560.93	2831.01	52.75	60.64
Ash	61.77	111.39	16.78	32.67
Crude protein	360.01	219.25	61.70	57.72
True protein	280.18	172.63	55.63	51.80
Crude fiber	622.62	693.03	45.54	54.97
Nitrogen-free extract	1415.99	1732.37	60.36	68.05
Ether extract	100.54	74.99	52.85	52.99
Fiber + N.-fr. extract	2038.61	2425.40	54.90	63.71

and with Pair III (Nos. 22 and 23), in the 4th ,8th and 12th periods. The quantitative collection of the excreta covered the last 7 days of the period, the first 8 days being regarded as preliminary. As in the previous year it seems desirable to consider first the results of the metabolism experiments.

Digestibility.—Table 10 shows the weights of the several nutrients digested and their percentage digestibility. The true protein was estimated, as in 1918, on the assumption that the feeding stuffs contained an average percentage of non-protein and that the latter was completely digested.

As in 1918, the digestibility of both the crude and true protein was considerably less in the low-protein than in the high-protein rations, the differences being of about the same order of magnitude as in the previous year. The digestibility of the crude fiber, on the other hand, with one exception (Period X), was greater in the low protein rations and the same is true without exception of the nitrogen-free extract and of the fiber + nitrogen-free extract. The digestibility of the ash and of the ether extract seems to follow that of the protein, being greater in the high-protein rations. Three of the trials, viz., Periods II, IV and VIII, show but slight differences in the digestibility of total dry matter, either as between the periods or between the high-protein and low-protein rations, corresponding in this respect with the results of 1918. In Periods VI, X and XII, however, the differences are more marked, the digestibility both of the dry matter and of all its ingredients, but especially of the ash and crude fiber, being relatively low. This is especially the case with the high-protein rations, particularly those of Calf No. 21, and suggests the influence of some abnormal condition.

As in the experiments of 1918, the observed digestibility of the dry matter and of the protein was less than that computed by the use of average digestion coefficients, as is shown in Table 11.

As regards the dry matter, the differences between the computed and observed digestibility are in general substantially the same in the high-protein and the low-protein rations while in the previous year they were greater in the low-protein rations. The differences may perhaps be ascribed to the relatively increased protein supply in the low-protein rations of 1919.

Exceptions to this statement, however, are to be noted in both animals in Period VI, with the high-protein animal in Period XII, and to a less degree with the low-protein animal in Period X, *i. e.*, in those periods whose results have already been queried.

As regards the total protein (N × 6.25) the differences are greater in the low-protein than in the high-protein rations in both years. Here again, however, the differences in Periods VI, X and XII appear exceptionally large.

TABLE 11

Computed digestibility of dry matter and crude protein

	Dry matter		Crude protein	
	Observed	Computed	Observed	Computed
	Per cent	Per cent	Per cent	Per cent
Pair II				
Period II				
No. 21 High protein	65.58	70.70	72.06	75.70
No. 20 Low protein	65.31	70.99	64.35	70.34
Period VI				
No. 21 High protein	51.67	68.47	63.65	76.30
No. 20 Low protein	58.88	69.39	55.92	72.34
Period X				
No. 21 High protein	60.32	66.32	72.28	72.76
No. 20 Low protein	57.08	67.49	57.64	66.13
Pair III				
Period IV				
No. 23 High protein	62.16	68.62	68.68	76.07
No. 22 Low protein	63.17	69.33	58 14	70.92
Period VIII				
No. 23 High protein	61.78	66.36	71.62	73.74
No. 22 Low protein	61.53	67.41	59.59	69.22
Period XII				
No. 23 High protein	52.75	64.52	61.70	74.56
No. 22 Low protein	60.64	66.93	57.72	69.12

Metabolizable energy.—In addition to the determinations made in the experiments of the previous year, the heats of combustion of the feed, feces and urine were determined and that of the methane excreted was estimated from the amounts of digested crude fiber and nitrogen-free-extract, assuming the energy thus lost to be, for crude fiber 0.614 Cals. and for the nitrogen-free extract 0.422 Cals. per gram.[1] From these data, the differences between the income and outgo of chemical energy, *i. e.*, the metabolizable energy, were as shown in Tables 12 and 13.

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[1] Based on Kellner's results as reported by the writer in "Principles of Animal Nutrition," pp. 325 and 330.

TABLE 12

Metabolizable energy per head

	Pair III			Pair IV	
	High-protein No. 21	Low-protein No. 20		High-protein No. 23	Low-protein No. 22
	Cals.	Cals.		Cals.	Cals.
Period II	7944	7697	Period IV	8434	7732
Period VI	6743	7533	Period VIII	9487	8123
Period X	10152	8863	Period XII	8898	9348

TABLE 13

Metabolizable energy per 1000 pounds live weight

	Pair III			Pair IV	
	High-protein No. 21	Low-protein No. 20		High-protein No. 23	Low-protein No. 22
	Therms	Therms		Therms	Therms
Period II	25.63	23.75	Period IV	23.04	22.41
Period VI	17.11	19.17	Period VIII	21.51	19.02
Period X	21.41	19.02	Period XII	17.87	18.96

These amounts of metabolizable energy differ in some instances materially from those computed from the digested organic matter by the method followed in the experiments of 1918, being lower in two-thirds of the cases. The computation of the metabolizable energy per gram of digested organic matter likewise gives decidedly variable results, ranging from 3.4 cals. to 4.2 cals. The percentages of the gross energy of the feed which were metabolizable are shown in Table 14.

It will be noted that these results run more or less parallel with those upon digestibility already discussed and that apparently abnormal results are shown in the same periods.

Computed net energy.—If from the amounts of metabolizable energy shown in Table 12, there be subtracted the heat increment

TABLE 14

Percentage of gross energy metabolizable

	Pair III			Pair IV	
	High-protein No. 21	Low-protein No. 20		High-protein No. 23	Low-Protein No. 22
Period II	55.11	55.02	Period IV	51.57	51.14
Period VI	40.75	44.64	Period VIII	50.65	48.73
Period X	52.35	45.70	Period XII	42.02	47.58

due to the consumption of the feed, estimated as in the experiments of 1918 from the dry matter consumed, the computed net energy of the several rations was as recorded in Table 15.

TABLE 15

Computed net energy per head

	Pair III			Pair IV	
	High-protein No. 21	Low-protein No. 20		High-protein No. 23	Low-protein No. 22
	Cals.	Cals.		Cals.	Cals.
Period II	4165	3928	Period IV	4203	3712
Period VI	2400	3035	Period VIII	4572	3635
Period X	5239	3803	Period XII	3315	3979

Intended and actual feed supply.—From the foregoing data and the average live weights for the first two and last two days of each digestion trial, the digestible true protein and net energy of the rations consumed per 1000 lbs. live weight in the digestion trials have been computed and compared with the amounts intended to be consumed, with the results shown in Table 16. In this table the amounts of protein are computed from those per head shown in Table 10, and those of net energy from those given in Table 15.

TABLE 16

Protein and energy supply per 1000 pounds live weight

	Pair II					Pair III			
	High-protein No. 21		Low-protein No. 20			High-protein No. 23		Low-protein No. 22	
	Protein Lbs.	Energy Therms	Protein Lbs.	Energy Therms		Protein Lbs.	Energy Therms	Protein Lbs.	Energy Therms
Period II					Period IV				
Intended	2.55	15.30	1.69	15.30	Intended	2.25	13.60	1.48	13.60
Actual	2.23	13.44	1.40	12.12	Actual	1.78	11.48	1.00	10.76
Period VI					Period VIII				
Intended	2.25	13.60	1.48	13.60	Intended	2.08	12.55	1.32	12.55
Actual	1.69	6.09	1.04	7.72	Actual	1.85	10.37	1.07	8.51
Period X					Period XII				
Intended	2.08	12.55	1.32	12.55	Intended	2.01	11.95	1.18	11.95
Actual	1.92	11.05	1.06	8.16	Actual	1.24	6.66	0.77	8.07

As in 1918, the actual feed supply as computed from the results of the digestion periods was less than was intended, owing chiefly to the differences in digestibility shown on page 244. In this year, with the relatively greater protein supply to the low-protein animals, no marked superiority in this respect of the high-protein rations over the low-protein ones was observed. The deficit was notably greater in those cases, already noted, in which the digestibility of the rations as a whole appears to have been abnormally low.

Gains of protein.—Small losses of urine occurred in five of the metabolism trials, the error thus caused being estimated by the authors at from 0.06 grams to 2.26 grams of nitrogen. Including these corrections, the daily gains of protein (N × 6.0) in each metabolism experiment, per head and per 1000 lbs. average live weight during the experiment, were as shown in Table 17.

TABLE 17

Daily gains of protein

Pair II			Pair III		
	No. 21 High-protein	No. 20 Low-protein		No. 23 High-protein	No. 22 Low-protein
Period II			Period IV		
Per head. Grms.	+69.24	+94.08	Per head. Grms.	+74.16	+30.36
Per 1000 live weight	+0.49	+0.64	Per 1000 live weight	+0.45	+0.19
Period VI			Period VIII		
Per head. Grms.	−76.62	−106.80	Per head. Grms.	+122.64	+41.16
Per 1000 live weight	−0.43	−0.60	Per 1000 live weight	+0.61	+0.21
Period X			Period XII		
Per head. Grms.	+178.20	−11.22	Per head. Grms.	−59.16	+41.46
Per 1000 live weight	+0.84	−0.05	Per 1000 live weight	−0.26	+0.19

The striking feature of these results is the marked irregularity of the nitrogen balance, some of the periods even showing a loss of protein, which appears unlikely in growing animals. It will be noted that these negative nitrogen balances occur in those periods in which the digestion results seem abnormal but the apparent

TABLE 18

Protein supply and daily gains per 1000 pounds live weight

	Pair II			Pair III	
	No. 21 High-protein	No. 20 Low-protein		No. 23 High-protein	No. 22 Low-protein
Period II	Age 152 days	Age 161 days	Period IV	Age 239 days	Age 239 days
	Lbs.	Lbs.		Lbs.	Lbs.
Digestible protein consumed	2.23	1.40	Digestible protein consumed	1.78	1.00
Estimated maintenance requirement	0.50	0.50	Estimated maintenance requirement	0.50	0.50
Available for growth	1.73	0.90	Available for growth	1.28	0.50
Observed gain of protein	0.49	0.64	Observed gain of protein	0.45	0.19
Estimated normal gain	0.79	0.75	Estimated normal gain	0.52	0.52
Period VI	Age 212 days	Age 221 days	Period VIII	Age 301 days	Age 301 days
Digestible protein consumed	1.69	1.04	Digestible protein consumed	1.85	1.07
Estimated maintenance requirement	0.50	0.50	Estimated maintenance requirement	0.50	0.50
Available for growth	1.19	0.54	Available for growth	1.35	0.57
Observed gain of protein	−0.43	−0.60	Observed gain of protein	0.61	0.21
Estimated normal gain	0.58	0.56	Estimated normal gain	0.42	0.42
Period X	Age 272 days	Age 281 days	Period XII	Age 361 days	Age 361 days
Digestible protein consumed	1.92	1.06	Digestible protein consumed	1.24	0.77
Estimated maintenance requirement	0.50	0.50	Estimated maintenance requirement	0.50	0.50
Available for growth	1.42	0.56	Available for growth	0.74	0.27
Observed gain of protein	0.84	−0.05	Observed gain of protein	−0.26	0.19
Estimated normal gain	0.46	0.45	Estimated normal gain	0.35	0.35

decrease in digestibility (or, in other words, the increased excretion of nitrogen in the feces) is insufficient to account for the negative nitrogen balance.

In Table 18, the actual gains of protein per day per 1000 pounds live weight shown by the metabolism experiments and the estimated normal gains at the several ages are compared with the amounts of digestible protein supplied (Table 16) and with the amounts available for growth after deducting the estimated maintenance requirement.

The remarkable fluctuations of the nitrogen balances, and particularly the negative balances, as well as the peculiar results regarding digestibility, in these trials, render the interpretation of the experiment difficult. One is tempted to disregard the four periods which show an apparent loss of body protein, particularly since the authors are inclined to ascribe the seemingly erratic results to the fact that the animals, in the absence of previous training, became somewhat nervous when placed in the elevated stalls and sometimes actually lost a few pounds in weight which was rapidly made up after their removal. If this be done, even although no specific justification for it appears in the recorded figures, the following comparisons of the feed supply and the gain of protein by the animals in the remaining periods may be made.

Range of protein supply in percentage of estimated minimum requirement	
High-protein rations	173% to 201%
Low-protein rations	91% to 116%
Range of energy supply in percentage of estimated requirement	
High-protein rations	79% to 88%
Low-protein rations	68% to 84%
Range of gain of protein in percentage of estimated normal gain	
High-protein rations	62% to 183%
Low-protein rations	37% to 85%

These selected results would seem to indicate that the protein supply in the low-protein rations was insufficient to support normal gains, while in several of the high-protein rations the surplus protein would seem to have stimulated growth in excess of the normal. It does not seem that the inferior results on the low-protein rations were due to lack of energy.

Such conclusions, however, are in conflict with these drawn from the live weights and measurements of the animals as reported in the following paragraphs.

INCREASE IN WEIGHT AND SIZE

Live weight.—As in 1918, the live weights were taken each 15 days upon two consecutive days. The increases per head and the cumulated increases are recorded in Table 19.

A fairly steady rate of growth was maintained by all the animals. The increase by the high-protein animal of Pair I (No. 19) and that by the low-protein animal of Pair IV (No. 24) was distinctly less than that made by the others but the percentage gain by No. 19 was relatively high. These somewhat small gains, however, offset each other, so that the absolute gains of the high-protein and low-protein lots as a whole were practically the same, but the percentage gain by the high-protein group was slightly

TABLE 19

Gains in live weight

At end of		Pair I				Pair II			
		No. 19 High-protein		No. 18 Low-protein		No. 21 High-protein		No. 20 Low-protein	
		In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated
		Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
First	15 days	11.5	11.5	18.5	18.5	17.0	17.0	23.0	23.0
Second	15 days	19.5	31.0	13.0	31.5	6.0	23.0	11.5	34.5
Third	15 days	8.5	39.5	14.0	45.5	30.5	53.5	14.5	49.0
Fourth	15 days	11.5	51.0	21.0	66.5	13.5	67.0	18.5	67.5
Fifth	15 days	15.0	66.0	13.0	79.5	23.0	90.0	21.5	89.0
Sixth	15 days	19.0	85.0	30.5	110.0	17.5	107.5	21.5	110.5
Seventh	15 days	13.5	98.5	11.0	121.0	21.0	128.5	13.5	124.0
Eighth	15 days	8.5	107.0	19.0	140.0	22.5	151.0	17.5	141.5
Ninth	15 days	27.0	134.0	27.5	167.5	35.0	186.0	32.5	174.0
Tenth	15 days	14.5	148.5	20.0	187.5	5.0	191.0	2.5	176.5
Eleventh	15 days	–2.5	146.0	7.5	195.0	20.0	211.0	35.0	211.5
Twelfth	15 days	25.0	171.0	22.5	217.5	17.5	228.5	15.0	226.5

TABLE 19—(*Continued*)

At end of		Pair III				Pair IV			
		No. 23 High-protein		No. 22 Low-protein		No. 25 High-protein		No. 24 Low-protein	
		In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated	In 15 days	Cumulated
		Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
First	15 days	16.5	16.5	12.0	12.0	18.5	18.5	13.0	13.0
Second	15 days	27.5	44.0	10.0	22.0	16.0	34.5	18.5	31.5
Third	15 days	13.5	57.5	23.0	45.0	9.0	43.5	7.5	39.0
Fourth	15 days	18.5	76.0	17.5	62.5	21.0	64.5	26.0	65.0
Fifth	15 days	16.5	92.5	14.0	76.5	13.5	78.0	5.0	70.0
Sixth	15 days	31.0	123.5	33.5	110.0	29.5	107.5	35.0	105.0
Seventh	15 days	11.5	135.0	15.0	125.0	13.5	121.0	1.5	106.5
Eighth	15 days	11.5	146.5	24.0	149.0	11.5	132.5	11.0	117.5
Ninth	15 days	37.5	184.0	28.5	177.5	40.0	172.5	25.0	142.5
Tenth	15 days	26.0	210.0	20.0	197.5	16.0	188.5	30.0	172.5
Eleventh	15 days	−10.0	200.0	0.0	197.5	5.0	193.5	−20.0	152.5
Twelfth	15 days	12.5	212.5	10.0	207.5	27.5	221.0	17.5	170.0

the greater. The mean gains per head by the two groups during the entire 180 days were practically identical, viz.,

	Total Lbs.	Per day Lbs.	Percentage of initial live weight
High-protein	208.5	1.16	74.1
Low-protein	207.5	1.14	69.1

The graph of the live weights of the animals (Fig. 2) likewise fails to show any consistent difference between the high-protein and the low-protein animals as regards rate of growth. The rate of growth also corresponds substantially with Eckles' results although the actual live weights were somewhat lower.

Height and girth.—Curiously, the greater total increase in size in these experiments was made by the low-protein animals. This is true either of the height or girth in each pair and of both in Pair III and on the average of the entire lots, as Table 20 shows. No obvious explanation of this peculiar result suggests itself.

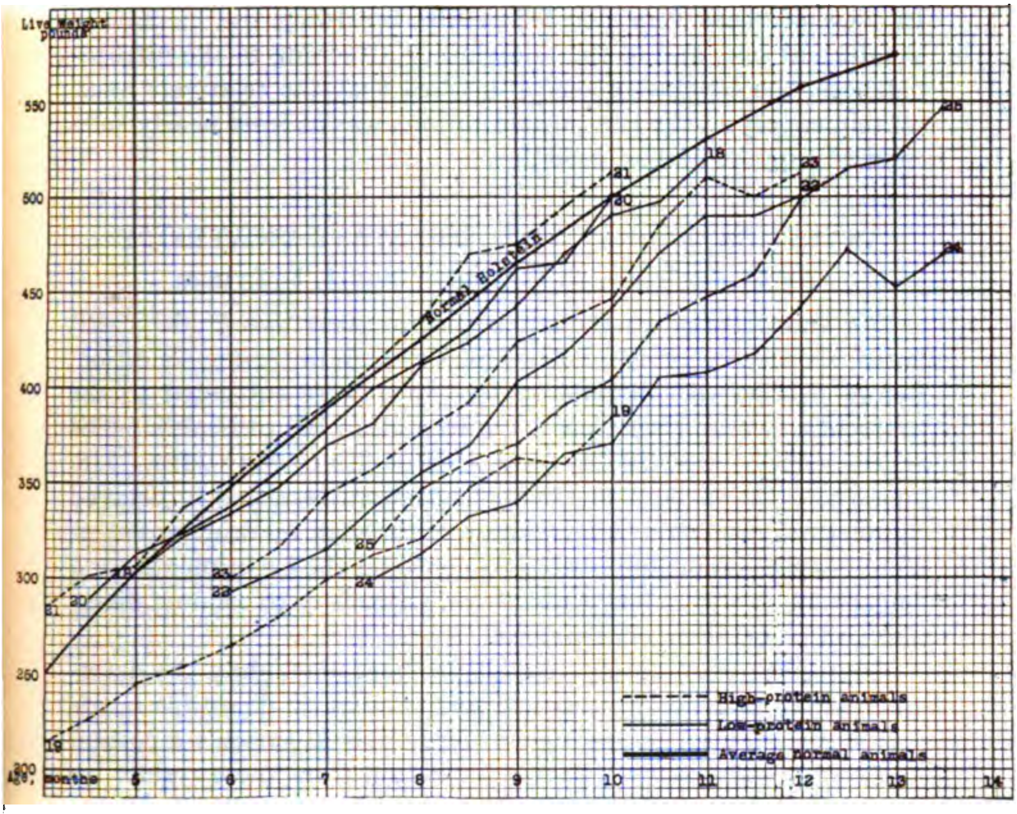

FIG. 2.—Live weights of animals. Experiments conducted at the Massachusetts station in 1919. The numbers appearing at the ends of curves in this figure refer to animals as numbered in Table 19.

TABLE 20

Total increase

		Height in inches	Girth in inches
Pair I	No. 19 High protein	6.5	9.0
	No. 18 Low protein	6.5	10.9
Pair II	No. 21 High protein	7.4	10.6
	No. 20 Low protein	7.5	11.0
Pair III	No. 23 High protein	5.9	9.0
	No. 22 Low protein	7.0	10.3
Pair IV	No. 25 High protein	5.4	9.0
	No. 24 Low protein	7.0	8.3
Means	High protein	6.3	9.4
	Low protein	7.0	10.1

In view of these very decided results regarding the increase in weight and size, and of the uncertainty attaching to the nitrogen balances, the conclusion seems justified that the relatively small protein supply in the low-protein rations was at least nearly sufficient to support normal growth.

INVESTIGATIONS AT THE OHIO STATE UNIVERSITY

By C. S. Plumb, C. T. Conklin and J. F. Lyman

The animals used in these experiments were two grade Shorthorns, six months of age, both thin, although in thrifty condition. Before putting the animals on feed they were subjected to the tuberculin test and were passed with a clean bill of health. The experiments covered 77 days, viz., March 9th to May 24th, 1918, inclusive. On account of the war situation, resulting in delayed shipment of materials and depletion of the staff by draft or enlistment, it was found impossible to continue the experiments for a longer time or with a larger number of animals or to conduct digestion and metabolism experiments.

The feeding stuffs used were all analyzed, including the determination of the non-protein. Their content of digestible nutrients was computed by the use of Henry and Morrison's digestion coefficients and their net energy estimated from these results by the method described in Bulletin No. 142 of the Pennsylvania Experiment Station. As thus computed, the average daily consumption of digestible protein and net energy per head and per 1000 pounds mean live weight during the experiment was as shown in Table 21. Upon these rations the two animals made identical gains in live weight, as Table 22 shows.

TABLE 21

Computed rations

	Digestible protein		Net energy	
	Per head	Per 1000 lbs. live weight	Per head	Per 1000 lbs. live weight
	Lbs.	Lbs.	Therms	Therms
Low protein	0.52	1.31	5.37	13.5
High protein	0.87	2.10	5.52	13.3

TABLE 22

Summary of gains

	High-protein	Low-protein	Eckles Shorthorn Heifers
Weight of calves March 9th	344 lbs.	328 lbs.	316 lbs.
Weight of calves May 24th	485 lbs.	469 lbs.	440 lbs.
Gain in weight	141 lbs.	141 lbs.	124 lbs.
Per cent of initial weight	41%	43%	
No. of days fed	77 days	77 days	
Average daily gain	1.83 lbs.	1.83 lbs.	1.61 lbs.

The rate of gain of the two animals was materially greater than that observed by Eckles for Shorthorn heifers of the same age. It would appear, therefore, that the low-protein ration contained sufficient protein so that the latter was not a limiting factor in growth.

The amounts of digestible protein computed to have been consumed compare as follows with the estimated minimum requirements per 1000 pounds live weight for animals of this age.

TABLE 23

Comparison with minimum requirement

	High-protein Lbs.	Low-protein Lbs.
Maintenance requirement	0.50	0.50
Estimated normal gain	0.56	0.56
Total minimum requirement	1.06	1.06
Computed digestible	2.10	1.31

These figures make it appear that even the low-protein animal received a considerable surplus of protein. The digestion experiments on similar rations at the Massachusetts and Virginia stations reported elsewhere in this paper, however, show that the digestibility of the protein was lower than was anticipated, although by widely varying amounts. The deficit in the high-protein rations varied from 8 to 33 per cent and that in the low-protein rations from 8 to 49 per cent. Omitting the highest and lowest figures in each case, the range was from 11 to 29 per cent with the high-protein rations and from 16 to 48 per cent with the low-protein. Omitting some questionable results (page 250), the mean deficit was 20 per cent and 24 per cent respectively. Even a deficit of 16 per cent in digestibility in the low-protein ration of this experiment, however, would reduce the protein supply to about the estimated minimum. While too much weight must not be given to such comparisons, they nevertheless tend to strengthen the conclusion that a protein supply but little in excess of the estimated minimum requirement sufficed to support a normal rate of growth.

INVESTIGATIONS AT THE VIRGINIA EXPERIMENT STATION

By C. W. Holdaway, W. B. Ellett and W. G. Harris

EXPERIMENTS OF 1918

ANIMALS

The animals used in this experiment were grade Holstein steers rather poorly developed for their age, their weights being considerably below the averages reported by Eckles (p. 226) for Holstein heifers. Nos. 72 and 73 did not appear as thrifty as the others and were therefore placed in different groups. No grouping by pairs is reported. The ages and initial weights of the animals were as follows:

TABLE 24

Ages and weights

Ration	No.	Initial age Months	Initial weight Pounds
High-protein	No. 71	8	213
	No. 72	8	195
Low-protein	No. 73	9	230
	No. 74	9	240

PERIODS AND RATIONS

The experiment was divided into two periods, following a preliminary feeding from March 1 to 25, 1918. The first experimental period extended from March 25, 1918, to June 30, 1918, or 97 days, and the second period from July 1, 1918, to September 25, 1918, or 87 days.

The rations for the first period were computed on the basis of the ages and live weights given above to correspond with the directions. Computed per 1000 pounds live weight they corresponded approximately with the age of the animals. (Table 25.) On July 1, 1918, the rations were changed to meet the estimated requirements of increased age and weight, the rations being com-

TABLE 25

Daily rations of first period

	High-protein		Low-protein	
	Calf No. 71	Calf No. 72	Calf No. 73	Calf No. 74
Age	8 Months	8 Months	9 Months	9 Months
Initial live weight	213 lbs.	195 lbs.	230 lbs.	240 lbs.
Rations per head, grams				
Oat straw	580	531	1252	1306
Alfalfa hay	1237	1132	696	725
Maize Meal	338	310	190	198
Linseed meal	181	165	101	106
Peanut meal	214	196	120	125
Starch	56	51	351	366

puted to correspond to the ages and weights on that date. Per head the rations were as shown in Table 26.

TABLE 26

Daily rations of second period

	High-protein		Low-protein	
	Calf No. 71	Calf No. 72	Calf No. 73	Calf No. 74
Age	11 Months	11 Months	12 Months	12 Months
Initial live weight	260 lbs.	225 lbs.	260 lbs.	270 lbs.
Rations per head, grams				
Oat straw	708	612	1416	1470
Alfalfa hay	1398	1210	646	670
Maize meal	382	330	176	184
Linseed meal	204	176	94	98
Peanut meal	240	208	110	116
Starch	90	78	574	596

DIGESTION AND METABOLISM EXPERIMENTS

During each of the two periods the digestibility of the total ration and the nitrogen balance were determined for each animal, the excreta being collected quantitatively for six days, viz., in the first period May 16-21 inclusive and in the second period Sept. 6-11 inclusive.

Digestibility.—Table 27 shows the actual weights of the several nutrients digested per day and per head together with the digestion coefficients.

TABLE 27

Amount digested per day and head

	High-protein				Low-protein			
	Calf No. 71		Calf No. 72		Calf No. 73		Calf No. 74	
	1st trial	2d trial	1st trial	2d trial	1st trial	2d trial	1st trial	2d trial
Weights digested *Grams*								
Dry matter	1537.6	1783.3	1324.7	1442.9	1500.7	1751.2	1594.8	1799.1
Organic matter	1473.2	1746.8	1268.6	1426.0	1447.2	1707.9	1537.3	1762.1
Crude protein	243.5	280.3	221.6	235.5	124.9	118.1	128.5	113.1
True protein	191.3	221.2	173.8	184.3	93.7	83.6	95.9	82.5
Crude fiber	365.3	424.6	303.0	374.2	432.5	459.6	459.0	435.1
Nitrogen-free extract	815.2	981.3	701.0	765.7	853.4	1092.8	905.3	1169.4
Ether extract	49.2	60.6	43.0	50.6	36.4	42.4	44.5	44.5
Per cent digested								
Dry matter	67.5	66.2	63.7	61.9	62.7	65.2	63.9	64.4
Organic matter	69.6	69.7	65.6	65.8	64.2	67.2	65.4	66.7
Crude protein	70.7	70.9	70.4	68.8	55.8	53.9	55.0	49.5
True protein	65.5	65.8	65.1	63.4	48.6	44.1	47.7	41.7
Crude fiber	56.4	55.4	51.3	56.4	60.4	59.7	61.6	54.5
Nitrogen-free extract	77.0	77.5	72.5	69.9	68.0	73.3	69.2	75.5
Ether extract	74.8	79.8	71.5	77.0	61.5	69.3	72.1	69.8

The digestion coefficients show that there was a marked depression of the digestibility of the protein in the low-protein rations which resulted in lowering the protein supply below the amount intended to be fed. Differences also appear in the digestibility of the crude fiber and nitrogen-free extract, the digestibility of the former being greater and that of the latter less in the low-protein rations in both trials, although the difference was not so marked in the second trial. It would seem that these differences are due chiefly to differences in the proportions of the different feeding stuffs consumed. On the other hand the digestibility of the total crude fiber plus nitrogen-free extract (carbohydrates) and of the total dry matter shows but slight differences.

As in the Massachusetts experiments, a comparison of the observed digestibility of the dry matter and crude protein of the rations with that computed by the use of average coefficients, as recorded in Table 28, reveals the fact that in every instance the observed digestibility of the crude protein is less than the computed, the difference in the percentage rising as high as 19 in one instance, and that the same thing is true to a lesser extent of the digestibility of the dry matter except in the case of Calf No. 71.

TABLE 28

Observed and computed digestibility of dry matter and crude protein

	Dry matter		Crude protein	
	Observed Per cent	Computed Per cent	Observed Per cent	Computed Per cent
First period				
High-protein				
No. 71	67.5	66.2	70.7	76.9
No. 72	63.7	66.2	70.4	76.9
Low-protein				
No. 73	62.7	66.0	55.8	70.6
No. 74	63.9	66.0	55.0	70.6
Second period				
High-protein				
No. 71	66.2	66.3	70.9	76.5
No. 72	61.9	66 3	68.8	76.5
Low-protein				
No. 73	65.2	67.7	53.9	68.9
No. 74	64.4	67.7	49.5	69.5

In the high-protein rations the apparent deficit in digestibility is slight, ranging from 0.1 to 4.4 for the dry matter and from 5.6 to 7.7 for the crude protein. In the low-protein rations, the deficit is not materially greater for the dry matter (2.1 to 3.3) but strikingly greater for the crude protein (14.8 to 20.0). For this reason, and also because the rations were computed on the initial weights in each period, the amounts of digestible protein and of net energy supplied to the animals per 1000 pounds live weight in the actual digestion trials were less than were intended, especially with the low-protein animals.

TABLE 29

Protein and energy supply per 1000 pounds live weight in digestion trials

	First trial		Second trial	
	Digestible true protein Lbs.	Net energy Therms	Digestible true protein Lbs.	Net energy Therms
High-protein				
Calf No. 71				
Intended	2.20	13.30	2.03	12.10
Observed	1.67	10.69[1] 11.24[2]	1.73	11.25[1] 11.96[2]
Calf No. 72				
Intended	2.20	13.30	2.03	12.10
Observed	1.75	11.24[1] 10.50[2]	1.65	11.10[1] 10.52[2]
Low-protein				
Calf No 73				
Intended	1.20	12.71	1.00	11.80
Observed	0.80	10.35[1] 10.08[2]	0.66	10.99[1] 11.59[2]
Calf No. 74				
Intended	1.20	12.71	1.00	11.80
Observed	0.78	10.33[1] 10.45[2]	0.62	10.80[1] 11.24[2]

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[1] As computed by the authors.

[2] As computed by the writer.

Intended and actual feed supply.—As already stated, the rations were intended to correspond to those proposed in the plan. In computing the rations the average coefficients reported by Henry & Morrison[1] were applied to the results of the analyses of the feeding stuffs. The digestibility of the true protein was estimated by deducting from the computed digestible crude protein the total amount of non-protein as reported in Bulletin No. 142 of the Pennsylvania Experiment Station. The net energy for the preliminary period was calculated from the data of the same Bulletin, allowing for differences in moisture content. For the rations of both digestion periods it was computed from the composition of the single feeding stuffs, by the use (apparently) of average digestion coefficients, by the method proposed by the writer. The writer has also computed the net energy from the total digestible organic matter of the rations as found in the digestion trials, using the same method as in the Massachusetts experiments (p. 232). The results are shown in Table 29.

Gains of protein.—In the digestion trials, the urine of the animals was also collected quantitatively and its nitrogen determined, thus giving the nitrogen balance and the gain of protein. Assuming the results of the digestion and metabolism trials to be representative, and computing the results per 1000 pounds from the corresponding live weights shown in Table 32, the gains of the body protein (N × 6.0) were as shown in Table 30.

TABLE 30

Daily gains of Protein (N × 6.0)

	High-protein		Low-protein	
	Calf No. 71	Calf No. 72	Calf No. 73	Calf No. 74
Per head				
First digestion trial	42.96 grms.	31.86 grms.	25.26 grms.	16.44 grms.
Second digestion trial	31.32 grms.	10.92 grms.	11.46 grms.	11.58 grms.
Per 1000 pounds live weight				
First digestion trial	0.376 lb.	0.321 lb.	0.216 lb.	0.134 lb.
Second digestion trial	0.246 lb.	0.098 lb.	0.091 lb.	0.087 lb.

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[1] "Feeds and Feeding" 15th Ed., p. 647.

In the first trial, the high-protein animals made a much greater gain of protein than did the low-protein ones. In the second trial, Nos. 72, 73 and 74 showed remarkably small gains, falling to about the same low level, while No. 71 showed a more normal increase. As compared with the estimated "normal" gain of protein, computed in the manner described on p. 226, and with the amounts of digestible protein available for growth the results were as stated in Table 31.

TABLE 31

Protein supply and daily gains per 1000 pounds live-weight

	High-protein		Low-protein	
	No. 71 Age 301 days	No. 72 Age 301 days	No. 73 Age 331 days	No. 74 Age 331 days
	Lbs.	Lbs.	Lbs.	Lbs.
First digestion trial				
Digestible protein consumed	1.67	1.75	0.80	0.78
Estimated maintenance requirement	0.50	0.50	0.50	0.50
Available for growth	1.17	1.25	0.30	0.28
Observed gain of protein	0.38	0.32	0.22	0.13
Estimated normal gain	0.42	0.42	0.39	0.39
	Age 414 days	Age 414 days	Age 444 days	Age 444 days
	Lbs.	Lbs.	Lbs.	Lbs.
Second digestion trial				
Digestible protein consumed	1.73	1.65	0.66	0.62
Estimated maintenance requirement	0.50	0.50	0.50	0.50
Available for growth	1.23	1.15	0.16	0.12
Observed gain of protein	0.25	0.10	0.09	0.09
Estimated normal gain	0.31	0.31	0.29	0.29

Of the high-protein animals receiving protein largely in excess of the estimated minimum requirements and net energy not greatly below the estimated requirements, No. 71 closely approached the estimated "normal" gain while No. 72 fell about 25% below it in the first trial and about 66% below it in the second trial. This animal was described by the authors as "unthrifty." On the other hand, both of the low-protein animals, on rations approaching the estimated requirements as regards energy, but with a protein supply distinctly below the estimated minimum, showed a rate of gain notably below the "normal."

LIVE WEIGHTS AND GAINS

The average live weights for 10 days at several intervals as compared with Eckles' results for the same ages, and the mean daily gains, are shown in Table 32.

TABLE 32

Weights and gains per head compared with normal

	High-protein			Low-protein		
	No. 71 Lbs.	No. 72 Lbs.	Eckles' average Lbs.	No. 73 Lbs.	No. 74 Lbs.	Eckles' average Lbs.
Live weights						
At beginning of experiment	214.5	190.3	435	230.1	240.6	475
At first digestion period	252.0	219.2	500	257.9	269.7	530
At second digestion period	281.4	246.9	592	278.5	294.4	609
Total gain as per cent of initial weight	31.2%	29.7%		21.0%	22.4%	
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
Mean daily gains						
From beginning to first digestion trial; 52 days	0.72	0.56	1.25	0.53	0.56	1.06
From first to second digestion trial; 113 days	0.26	0.25	0.81	0.18	0.22	0.70
From beginning to second digestion trial; 165 days	0.41	0.35	0.95	0.30	0.33	0.81

In proportion to their live weight (Table 33) the animals showed in the first period a tendency to more rapid gain in weight than the computed normal, *i. e.*, they tended to make up lost time. In the second period, however, they fell much below the normal rate of increase, this difference being much larger on the low protein rations.

On the whole, both the live weight results and the nitrogen balances show a distinct advantage on the side of the high-protein

TABLE 33

Daily gain per 1000 average live weight at middle of period

	High-protein			Low-protein		
	Calf No. 71	Calf No. 72	Eckles' average	Calf No. 73	Calf No. 74	Eckles' average
From beginning to first digestion period (52 days)	3.09	2.72	2.67	2.19	2.20	2.11
From first to second digestion period (113 days)	0.98	1.06	1.48	0.69	0.78	1.23

rations but indicate that even these animals failed to gain weight or store protein at the normal rate for their age and size. Before ascribing these differences to the difference in the protein supply, however, it is necessary to consider whether the rations furnished sufficient energy.

In the first period, it appears from Table 29 that the net energy in both the high-protein and the low-protein rations was distinctly less than the estimated requirement yet the high-protein animals appear to have made almost a normal gain of protein (Table 31) and a super-normal gain of live weight for their size (Table 33). The low-protein animals, on the contrary, which received slightly less protein than the estimated minimum requirement, showed a distinctly sub-normal gain of protein but a nearly normal relative gain of live weight.

In the second and longer period, the energy supply of all the animals was nearly equal to the estimated requirement. In this period No. 71 of the high-protein animals made almost a normal gain of protein, while No. 72 (the "unthrifty" animal) showed a very low gain, but both animals made about ⅔ the estimated normal increase in live weight. The low protein animals, whose protein supply was about ⅔ of the estimated minimum requirement, showed a notably small increase in both body protein and in live weight.

It would appear, then, despite some irregularities and uncertainties, that the protein content of the low-protein rations, which was considerably lower than was intended, was a limiting factor in the growth of these animals.

INVESTIGATIONS AT THE VIRGINIA EXPERIMENT STATION (CONTINUED)

EXPERIMENTS OF 1919

ANIMALS

For this experiment four pure-bred Holstein bull calves were selected, all of them relatively large animals. No's 2 and 3 seemed less thrifty than the other two and were therefore placed in different groups. The ages and weights at the beginning of the experiment, on June 1st, 1919, were as shown in Table 34. No grouping of the animals by pairs is reported. The live weights are notably greater than those reported by Eckles for light-fed Holstein calves of corresponding ages.

TABLE 34

Description of animals

		Date of birth	Age, June 1, 1919 days	Weight June 1, 1919 lbs.
High-protein	No. 1	December 16, 1918	166	440
	No. 2	November 29, 1918	183	395
Low-protein	No. 3	December 19, 1918	163	475
	No. 4	December 13, 1918	169	447

PERIODS AND RATIONS

The rations as computed were intended to correspond to those given in the plan. As was the case with the experiments of the previous year, the digestion trials showed that they were actually somewhat lower in net energy and decidedly lower in digestible protein than was intended.

The first rations computed, the feeding of which was begun on June 1st, proved to be too bulky for the animals to consume completely. Accordingly a portion of the oat straw was withdrawn from the ration and starch substituted for it. The feeding of this new ration began on June 29 and extended to August 1. On that date the rations were increased in amount to correspond with the increase in weight of the animals but the amounts of protein and energy per 1000 pounds live weight were intended to be the same as for the rations of the first period. The second period extended from August 1st to September 21st inclusive. The respective rations for the two periods are shown in Tables 35 and 36.

TABLE 35

Daily rations of first period

	High-protein		Low-protein	
	Calf 1	Calf 2	Calf 3	Calf 4
Age, June 29, 1919	194 days	211 days	191 days	197 days
Live weight for the 8 days ending June 28, 1919	480 lbs.	414 lbs.	487 lbs.	470 lbs.
Rations Per Head	Grams	Grams	Grams	Grams
Oat straw	1270	1134	1878	1814
Alfalfa hay	1724	1452	1161	1134
Maize meal	943	822	645	631
Linseed meal	425	376	291	284
Peanut meal	503	439	347	340
Starch	610	532	957	929

TABLE 36

Daily rations of second period

	High-protein		Low-protein	
	Calf 1	Calf 2	Calf 3	Calf 4
Age August 1st	227 days	244 days	224 days	230 days
Live weight for the 8 days ending July 31	527 lbs.	453 lbs.	516 lbs.	508 lbs.
Rations Per Head	Grams	Grams	Grams	Grams
Oat straw	1451	1225	2041	1996
Alfalfa hay	1905	1633	1270	1225
Maize meal	1056	907	695	680
Linseed meal	475	411	319	312
Peanut meal	567	489	376	369
Starch	680	588	1524	1496

The computations of the rations were based upon analyses of the feeding stuffs used, allowance being made in the second period for changes in the moisture content of the feeds.

DIGESTION AND METABOLISM EXPERIMENTS

As already stated, the digestibility of the total ration and the nitrogen balance were determined for each animal during each of the two periods, the excreta being collected quantitatively for the seven days July 15 to 21 and September 15 to 21 respectively.

Digestibility.—Table 37 shows the actual weights of the several nutrients digested per day and head together with the digestion coefficients:

TABLE 37

Amount digested per day and head

	High-protein				Low-protein			
	Calf No. 1		Calf No. 2		Calf No. 3		Calf No. 4	
	1st trial	2d trial	1st trial	2d trial	1st trial	2d trial	1st trial	2d trial
Weights digested								
Grams								
Dry matter	3156.2	3795.6	2826.6	3205.8	2757.1	3806.9	2984.8	3723.8
Organic matter	3080.7	3680.2	2740.4	3124.0	2697.7	3705.8	2924.8	3661.3
Crude protein	441.2	507.0	400.2	450.4	233.5	284.9	239.6	261.0
True protein	383.9	443.7	350.8	396.0	189.4	237.2	201.0	214.6
Crude fiber	550.8	667.0	494.8	535.5	474.6	601.6	507.3	659.9
Nitrogen-free extract	1969.6	2372.0	1742.3	2022.9	1907.4	2725.6	2082.3	2646.9
Ether extract	119.1	134.2	103.9	115.2	82.2	93.7	95.6	93.7
Per cent digested								
Dry matter	65.0	70.1	67.1	69.1	58.9	68.8	65.5	68.9
Organic matter	66.9	71.6	68.5	71.0	60.5	70.1	67.5	70.9
Crude protein	60.3	62.7	63.2	64.8	43.8	49.4	46.1	46.5
True protein	56.7	59.6	60.1	61.8	38.7	44.9	41.7	41.6
Crude fiber	51.3	55.5	53.0	52.4	42.3	49.4	46.6	55.6
Nitrogen-free extract	73.8	79.8	75.0	79.4	70.7	80.9	77.5	80.3
Ether extract	82.0	83.2	82.2	83.2	72.5	76.7	86.5	78.6

As in the experiments of the previous year, the results show a distinct depression of digestibility in the low-protein rations, particularly as regards the digestibility of the protein and the crude fiber. This resulted in lowering the protein supply of the low-protein group considerably below the amount intended to be fed. In distinction from the results of the previous year, the digestibility of the crude fiber also shows a distinct depression, except in one instance, while the figures for the nitrogen-free extract show but slight differences. The digestibility in the second trial is distinctly higher than in the first, while in 1918 little difference was noted.

As in all the other experiments of the series, the actual digestibility of the mixed rations, as to both dry matter and protein, differed from that computed by the use of average digestion coefficients, as appears from the comparisons in Table 38.

TABLE 38

Observed and computed digestibility of dry matter and crude protein

	Dry matter		Crude protein	
	Observed	Computed	Observed	Computed
First period				
High-protein				
No. 1	65.0	71.3	60.3	78.1
No. 2	67.1	71.4	63.2	78.2
Low-protein				
No. 3	58.9	71.0	43.8	75.2
No. 4	65.5	71.0	46.1	75.3
Second period				
High-protein				
No. 1	70.1	71.3	62.7	78.0
No. 2	69.1	71.4	64.8	78.1
Low-protein				
No. 3	68.8	73.3	49.4	75.1
No. 4	68.9	73.4	46.5	75.1

The high-protein rations show only small differences in the digestibility of the dry matter (1.2 to 6.3) but much more marked ones in that of the crude protein (13.3 to 17.8). In the low-protein rations the discrepancy is somewhat greater in the dry matter (4.5 to 12.1) and strikingly large in the crude protein (25.7 to 31.4). The supply of digestible protein and of net energy was therefore much less than was intended, particularly in the low-protein rations.

Intended and actual feed supply.—The digestible true protein and the net energy of the rations consumed in the digestion trials has been computed in the same way as in the experiments of the previous year, the energy being computed in the two different ways. The results computed per 1000 pounds live weight at the time of the digestion trials were as follows:

TABLE 39

Protein and energy supply per 1000 lbs. live weight in digestion trials

	First trial		Second trial	
	Digestible true protein	Net energy	Digestible true protein	Net energy
	Lbs.	Therms	Lbs.	Therms
High-protein				
Calf No. 1				
Intended	2.40	14.50	2.40	14.50
Observed	1.71	13.75[1] 11.73[2]	1.60	12.41[1] 12.06[2]
Calf No. 2				
Intended	2.40	14.50	2.40	14.50
Observed	1.82	13.96[1] 12.43[2]	1.70	12.70[2] 12.10
Low-protein				
Calf No. 3				
Intended	1.62	14.50	1.62	14.50
Observed	0.85	12.63[1] 9.33[2]	0.91	13.17[1] 12.82[2]
Calf No. 4				
Intended	1.62	14.50	1.62	14.50
Observed	0.90	12.36[1] 11.40[2]	0.82	12.73[1] 12.66[2]

[1] As computed by the authors.

[2] As computed by the writer.

Gains of protein.—Computed from the nitrogen balances of the two metabolism trials and from the corresponding live weights at those dates, as shown in Tables 35 and 36, the daily gains of body protein (N × 6.0) per head and per 1000 pounds live weight were as shown in Table 40.

TABLE 40

Daily gains of protein (N × 6.0)

	High-protein		Low-protein	
	Calf No. 1	Calf No. 2	Calf No. 3	Calf No. 4
Per head				
First digestion trial	146.82 grms.	90.54 grms.	43.56 grms.	65.34 grms.
Second digestion trial	122.70 grms.	64.14 grms.	83.70 grms.	58.20 grms.
Per 1000 pounds live weight				
First digestion trial	0.65 lb.	0.47 lb.	0.20 lb.	0.29 lb.
Second digestion trial	0.44 lb.	0.28 lb.	0.32 lb.	0.22 lb.

The results as compared with the estimated normal gain of protein, computed as in previous cases, and with the amounts of digestible protein available for growth, are shown in Table 41.

In the first trial, the gains of protein were notably greater by the high-protein animals, closely approaching or even exceeding the estimated normal, while the low-protein animals reached only one-half to one-third the normal on rations supplying somewhat less than the estimated minimum requirement for normal growth. In the second trial, one of the high-protein animals (No. 1) continued to show a normal gain but the other (No. 2) dropped to the level of the low-protein animals, all three being much below the normal. In other words, the protein supply seems to have been the limiting factor in the growth of the low-protein animals.

LIVE WEIGHTS AND GAINS

The rations fed were computed upon the initial live weights of each animal on the average of the eight days preceding the beginning of each period. These weights, together with those for the eight days preceding each digestion trial, and the corresponding gains as compared with Eckles' results for the same ages*, are recorded in Table 42.

*Mean age of the two animals.

TABLE 41

Protein supply and daily gains per 1000 pounds live weight

	High-protein		Low-protein	
	No. 1 Age 210 days	No. 2 Age 227 days	No. 3 Age 207 days	No. 4 Age 213 days
	Lbs.	Lbs.	Lbs.	Lbs.
First digestion trial				
Digestible protein consumed	1.71	1.82	0.85	0.90
Estimated maintenance requirement	0.50	0.50	0.50	0.50
Available for growth	1.21	1.32	0.35	0.40
Observed gain of protein	0.65	0.47	0.20	0.29
Estimated normal gain	0.59	0.55	0.60	0.58
	Age 272 days	Age 289 days	Age 269 days	Age 275 days
	Lbs.	Lbs.	Lbs.	Lbs.
Second digestion trial				
Digestible protein consumed	1.60	1.70	0.91	0.82
Estimated maintenance requirement	0.50	0.50	0.50	0.50
Available for growth	1.10	1.20	0.41	0.32
Observed gain of protein	0.44	0.28	0.32	0.22
Estimated normal gain	0.46	0.44	0.47	0.46

The gains in live weight per 1000 pounds, as shown in Table 43, are computed upon the basis of the live weight at the middle of each period. For example, in case of Calf No. 1, in the first period the weight is taken to be the average of 480 pounds and 496 pounds and that for the second period the average of 496 pounds and 527 pounds. Table 43 shows the live weights and gains computed in this manner as compared with Eckles' results for the same age.

Not only were the animals, as already noted, heavy for their age at the start of the experiments but their gains were both absolutely and relatively greater than those reported by Eckles for animals of the same bread. It would seem that they had an

TABLE 42

Live weights and gains per head compared with normal

	High-protein			Low-protein		
	No. 1	No. 2	Eckles' average	No. 3	No. 4	Eckles' average
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
Live weights						
At beginning of experiment	480	414	381	487	470	369
At first digestion trial	496	426	400	493	490	389
At beginning of 2d period	527	453	421	516	508	411
At second digestion trial	612	514	480	573	580	468
Total gain as per cent of initial weight	27.5%	24.2%		17.7%	23.4%	
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
Daily gains						
From beginning to first digestion trial; 16 days	1.00	0.75	1.19	0.38	1.25	1.25
From first digestion trial to beginning of 2d period; 17 days	1.82	1.59	1.24	1.35	1.06	1.29
From beginning of 2d period to second digestion trial; 45 days	1.89	1.36	1.31	1.26	1.59	1.27
For entire experiment; 78 days	1.69	1.29	1.27	1.10	1.41	1.27

unusual capacity for growth. The rapid increase can hardly be attributed to fattening since the computations of Table 39 show the amounts of net energy consumed to have been materially lower than the estimated requirements for normal growth with no considerable fattening and but slightly greater on the whole for the high-protein than for the low-protein animals.

On the whole the live weight results seem to confirm the conclusion drawn from the nitrogen balances that the unintended reduction of the protein supply of Nos. 3 and 4 below the estimated minimum requirement resulted in a rate of growth less than the normal.

TABLE 43

Daily gain of weight per 1000 lbs. average live weight at middle of period

	High-protein			Low-protein		
	Calf No. 1	Calf No. 2	Normal	Calf No. 3	Calf No. 4	Normal
	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.
From beginning to first digestion trial	2.05	1.79	3.04	0.78	2.60	3.30
From first digestion trial to beginning of 2d period	3.55	3.61	3.02	2.65	2.12	3.12
From beginning of 2d period to second digestion trial	3.32	2.81	2.90	2.31	2.92	2.89
For entire experiment	3.10	2.78	2.95	2.08	2.69	3.03

DISCUSSION OF RESULTS

Method of expression.—It has been a quite common practice to express the results of investigations on the protein requirements of animals in terms of a ratio or percentage. In experiments on animal nutrition the so-called nutritive ratio, originally devised as an aid to the practical feeder in the computation of rations, has found wide application. In more strictly biological investigations, much use has been made of a similar relation, viz., the percentage of the total energy of the feed which is contained in its protein. For example, an animal receiving feed containing 16 per cent of its energy in the form of protein has been regarded as being on a higher protein level than one whose feed contained only 12 per cent of its energy in the form of protein. For many purposes this is a convenient method of expression but it is liable to be misleading unless its limitations are recognized.

Growth is not supported by ratios or percentages but by protein and energy. If a feed with a low percentage of its energy in the form of protein gives inferior results, as measured by live weight, it is not because of this low percentage in itself but because the amount of the feed consumed fails to supply either enough grams of protein or enough calories of total energy, or both. Failure to realize this vitiates the conclusions drawn from numerous experiments. The error is of the same nature as that which, as Osborne and Mendel[1] have recently pointed out, likewise vitiates many investigations regarding vitamines. It is only when the energy supply of the animals to be compared is the same, as the same authors[2] have insisted, that a comparison of percentages of protein calories is significant. For this reason stress was laid in the plan for these experiments upon equality of energy supply, although the efforts in that direction did not prove particularly successful so far as can be judged from the evidence of the balance experiments. The writer believes that in discussing experiments of this sort confusion of thought may often be avoided by dealing with quantities of protein and energy rather than with proportions, particularly in the comparison of the actual results with the normal rate of growth.

THE RESULTS OF THE METABOLISM TRIALS

The object of the metabolism trials was, first to determine the actual feed supply with greater accuracy than could be hoped for by the use of average digestion coefficients and second, to determine the gain of protein (nitrogen balance) of the animals as a measure of the true growth rather than to depend entirely on the live weights. The determinations of the nitrogen balance seemed also to offer a further probable advantage of being less dependent upon equality in the energy supply than are comparisons based on the live weight, provided of course, that there was not a deficiency of energy. If the lower energy supply was sufficient to protect the protein from being katabolized, an additional amount of energy might be expected to result in an increase of live weight due to fattening without any material influence upon the gain of protein.

As appears from the foregoing records of the experiments, however, these presumable advantages proved more or less illusory for various reasons.

The digestibility of the rations.—The results of the digestion trials seem to show very clearly that the actual feed supply of experimental animals may differ materially from that computed by the use of average digestion coefficients both as regards the total feed (energy) and especially as regards protein. This is most obvious in the case of the low-protein rations, where the familiar depression of digestibility caused by a large proportion of carbohydrates was very manifest, but it was true also of the high-protein rations. Table 44 summarizes the amounts of digested true protein and of net energy (computed in the manner described in connection with the several experiments) actually consumed according to the testimony of the digestion trials compared with that computed and intended to have been consumed.

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[1] *Jour. Biol. Chem.*, 45 (1921), 283.

[2] *Jour. Biol. Chem.*, 26 (1916), 1.

The results shown in Table 44 are more or less fluctuating but on the average of all the trials the digestibility of both the protein and energy of the high-protein rations was about 80 per cent of that computed from the actual composition of the feeding stuffs by the use of average digestion coefficients. Ewing and his associates[1] have observed similar discrepancies between the observed and computed digestibility of the mixed rations of cattle and Rubner[2] reports similar observations on a dog, with which, however, mixtures of vegetable foods showed a higher digestibility than was computed. On the other hand Hummel[3] in experiments on cows, using, however, only four-day collection periods, observed no significant differences. In the case of the low-protein rations in these experiments the reduction of the energy supply below that computed was little more than in the high-protein rations, viz., 24 per cent as compared with 20 per cent. The digestibility of the protein, on the contrary, fell much lower than in the high-protein rations, averaging only 68 per cent of that computed. This phenomenon also is a familiar one. The general teaching of the experiments is substantially the same whether the somewhat questionable results of the Massachusetts experiments of 1919 are included or excluded.

The gains of protein.—In presenting on previous pages the results obtained at the several stations the attempt has been made to compare the gain of protein as shown by the nitrogen balances with the amount of protein available to sustain growth after the maintenance requirement was satisfied. In the absence of any more satisfactory data, the maintenance requirement of protein has been assumed to have been uniformly 0.50 per thousand

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[1] *Journal of Agr'l Research*, 13 (1918), 611.

[2] *Arch.* (*Anat u.*) *Physiol.*, 1918, 135.

[3] *Minnesota Expt. Sta.*, *Bul.* 99 (1907), 121-132.

TABLE 44

Protein and energy supply per 1,000 pounds live weight compared with that computed

	High-protein rations						Low-protein rations					
	Protein			Energy			Protein			Energy		
	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed
	Lbs.	Lbs.	Percent	Therms	Therms	Per cent	Lbs.	Lbs.	Per cent	Therms	Therms	Per cent
Massachusetts Station, 1918												
Pair III	2.00	1.74	87	11.80	8.84	75	1.00	0.84	84	11.80	7.26	62
Pair IV, first trial	2.03	1.80	89	12.10	8.53	70	1.07	0.98	92	12.10	8.62	71
Pair IV, second trial	2.00	1.73	87	11.80	8.72	74	1.00	0.70	70	11.80	7.52	64
Means	2.01	1.76	88	11.90	8.70	73	1.02	0.84	82	11.90	7.80	66
Massachusetts Station, 1919												
Pair II, Period II	2.55	2.23	87	15.30	13.44	88	1.69	1.40	83	15.30	12.12	79
Pair II, Period VI	(2.25)	(1.69)	(75)	(13.60)	(6.09)	(45)	(1.48)	(1.04)	(70)	(13.60)	(7.72)	(57)
Pair II, Period X	2.08	1.92	92	12.55	11.05	88	(1.32)	(1.06)	(80)	(12.55)	(8.16)	65)
Pair III, Period IV	2.25	1.78	79	13.60	11.48	84	1.48	1.00	68	13.60	10.76	79
Pair III, Period VIII	2.08	1.85	89	12.55	10.37	83	1.32	1.07	81	12.55	8.51	68
Pair III, Period XII	2.01	1.24	62	11.95	6.66	56	1.18	0.77	65	11.95	8.07	68
Means	2.20	1.79	81	13.26	9.85	74	1.41	1.06	75	13.26	9.52	72
Corrected means	2.24	1.95	87	13.50	11.59	86	1.42	1.06	77	13.35	9.87	74

TABLE 44 (*Continued*)

	High-protein rations						Low-protein rations					
	Protein			Energy			Protein			Energy		
	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed	Computed	Actual	Actual ÷ computed
	Lbs.	Lbs.	Per cent	Therms	Therms	Per cent	Lbs.	Lbs.	Per cent	Therms	Therms	Per cent
Virginia Station, 1918												
Nos. 71 and 74, first trial	2.20	1.67	76	13.30	11.24	85	1.20	0.78	65	12.71	10.45	82
Nos. 71 and 74, second trial	2.03	1.73	85	12.10	11.96	99	1.00	0.62	62	11.80	11.24	95
Nos. 72 and 73, first trial	2.20	1.75	80	13.30	10.50	79	1.20	0.80	67	12.71	10.08	79
Nos. 72 and 73, second trial	2.03	1.65	81	12.10	10.52	87	1.00	0.66	66	11.80	11.59	98
Means	2.12	1.70	80	12.70	11.06	87	1.10	0.71	65	12.26	10.84	88
Virginia Station, 1919												
Nos. 1 and 4, first trial	2.40	1.71	71	14.50	11.73	81	1.62	0.90	56	14.50	11.40	79
Nos. 1 and 4, second trial	2.40	1.60	67	14.50	12.06	83	1.62	0.82	51	14.50	12.66	87
Nos. 2 and 3, first trial	2.40	1.82	76	14.50	12.43	86	1.62	0.85	52	14.50	9.32	64
Nos. 2 and 3, second trial	2.40	1.70	71	14.50	12.10	83	1.62	0.91	56	14.50	12.82	88
Means	2.40	1.71	71	14.50	12.08	83	1.62	0.87	54	14.50	11.55	80
Means of all	2.18	1.74	80	13.09	10.42	80	1.29	0.87	68	12.98	9.93	76
Corrected means of all*	2.19	1.78	81	13.15	10.86	80	1.29	0.87	68	13.00	10.02	77

*Omitting doubtful results in 1919.

TABLE 45

Protein available for growth compared with normal and with observed gain of protein

	High-protein								Low-protein							
	Animal	Period	Age-days	Feed protein available: Total per 1000	Feed protein available: Per cent of normal gain	Normal gain per 1000	Observed gain per 1000	Per cent of available protein utilized	Animal	Period	Age-days	Feed protein available: Total per 1000	Feed protein available: Per cent of normal gain	Normal gain per 1000	Observed gain per 1000	Per cent of available protein utilized
Massachusetts, 1918	5	6	386	1.24	376	0.33	0.57	46	6	6	386	0.34	103	0.33	0.41	121
	7	5	372	1.30	382	0.34	0.35	27	8	5	372	0.48	141	0.34	0.29	60
	7	6	394	1.23	373	0.33	0.48	39	8	6	394	0.20	61	0.33	0.26	130
Total and means				3.77	377	1.00	1.40	37				1.02	102	1.00	0.96	94
Massachusetts, 1919	21	II	152	1.73	219	0.79	0.49	28	20	II	161	0.90	120	0.75	0.64	71
	21	VI	212	1.19	205	0.58	−0.43		20	VI	221	0.54	96	0.56	−0.60	
	21	X	272	1.42	309	0.46	0.84	59	20	X	281	0.56	124	0.45	−0.05	
	23	IV	239	1.28	246	0.52	0.45	35	22	IV	239	0.50	96	0.52	0.19	38
	23	VIII	301	1.35	321	0.42	0.61	45	22	VIII	301	0.57	136	0.42	0.21	37
	23	XII	361	0.74	211	0.35	−0.26		22	XII	361	0.27	77	0.35	0.19	70
Totals and means*				5.78	264	2.19	2.39	41				2.24	110	2.04	1.23	55

TABLE 45—(*Continued*)

	High-protein								Low-protein							
	Animal	Period	Age-days	Feed protein available		Normal gain per 1000	Observed gain per 1000	Per cent of available protein utilized	Animal	Period	Age-days	Feed protein available		Normal gain per 1000	Observed gain per 1000	Per cent of available protein utilized
				Total per 1000	Per cent of normal gain							Total per gain	Per cent of normal 1000			
Virginia, 1918																
	71	1	301	1.17	279	0.42	0.38	32	73	1	331	0.30	77	0.39	0.22	73
	71	2	414	1.23	397	0.31	0.25	20	73	2	444	0.16	55	0.29	0.09	56
	72	1	301	1.25	298	0.42	0.32	26	74	1	331	0.28	72	0.39	0.13	46
	72	2	414	1.15	371	0.31	0.10	9	74	2	444	0.12	41	0.29	0.09	75
Totals and means				4.80	329	1.46	1.05	22				0.86	67	1.36	0.53	62
Virginia, 1919																
	1	1	210	1.21	205	0.59	0.65	54	3	1	207	0.35	58	0.60	2.20	57
	1	2	272	1.10	239	0.46	0.44	40	3	2	269	0.41	87	0.47	0.32	78
	2	1	227	1.32	240	0.55	0.47	36	4	1	213	0.40	69	0.58	0.29	73
	2	2	289	1.20	273	0.44	0.28	23	4	2	275	0.32	70	0.46	0.22	69
Totals and means				4.83	237	2.04	1.84	38				1.48	70	2.11	1.03	70

*Omitting Period VI for both high and low protein, Period X for the low-protein and Period XII for the high-protein.

on the strength of results reported elsewhere by the writer.[1] It is fully recognized that this figure is uncertain and may be considerably in error in individual cases.

The results of these comparisons are summarized in Table 45, in which the protein available for growth after the estimated maintenance requirement is provided for is compared with the observed gain of protein and with the normal gain computed in the manner described on page 226.

Comparing first the results on the low-protein with those on the high-protein animals, it appears that except in a single instance out of fourteen (excluding the apparent negative gains in the Massachusetts experiments of 1919) the animals receiving the high-protein rations showed a greater gain of protein per 1000 than did their mates on the low-protein rations. Comparing the means for the several years, it appears that the gains of protein made by the low-protein groups were the following percentages of those made by the high-protein groups:

Massachusetts experiments of 1918	68.6%
Virginia experiments of 1918	50.5%
Massachusetts experiments of 1919	51.5%
Virginia experiments of 1919	56.0%

On the other hand, a comparison of the gains of protein by the low-protein animals with the estimated normal gain of protein presents a somewhat different picture. The individual results are strikingly variable but some indication of their general trend may perhaps be secured from the means for the several groups.

In the Massachusetts experiments, omitting, as in the discussion of digestibility, the doubtful periods in 1919, it appears that on the average of the remaining metabolism experiments the digested protein available for growth was but slightly greater than the estimated normal increase of body protein. On this amount in 1918 almost normal growth (96%) appears to have been made, which is equivalent to the utilization of 94% of the available protein. In 1919, on the contrary, the increase of body protein was much less than the assumed normal growth (60%, equivalent to 65% utilization). On the high-protein rations, on the other hand, the average increase of body protein was decidedly greater than the assumed normal and this was also true in four out of the seven individual cases. Since, however, these rations obviously supplied a surplus of protein, the percentage utilization is apparently low.

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[1] "Nutrition of Farm Animals," page 327.

In the experiments at the Virginia Station, on the other hand, the estimated protein available for growth was on the average only about 70 per cent of the normal protein gain and the increase of body protein was only 39 per cent of the normal in 1918 and 49 per cent in 1919, or 45 per cent on the average of both years, while the energy supply of the low-protein animals was only slightly less (97%) than that of the high-protein group. It seems clear that the smaller gains were due, at least in greater part, to an actual deficiency of protein due to the reduced digestibility of the rations.

The following is a condensed comparison of the foregoing results:

	Available protein in per cent of "normal" gain	Gain of protein in per cent of "normal" gain
Massachusetts experiments of 1918	102%	96%
Massachusetts experiments of 1919	110%	60%
Virginia experiments of 1918	67%	39%
Virginia experiments of 1919	70%	49%

A curious fact is that the deficient protein supply in the Virginia experiments seems to have so affected the power of growth that the percentage utilization of the protein available for growth was only 60 to 70 per cent whereas one would have expected that this diminished supply would have been used with the utmost economy.

It remains to be considered whether the inferior results on the low-protein as compared with the high-protein rations were due to lack of sufficient protein or to a deficient energy supply. It is difficult to answer this question very satisfactorily. In the Massachusetts experiments the average energy supply of the low-protein animals in 1918 was 90 per cent of that of the high-protein animals (Table 44), yet the low-protein animals made an almost normal gain. In 1919 the energy supply of the low-protein group was 85 per cent of that of the high-protein. The difference between the two years seems scarcely sufficient to account for the notably inferior results in 1919. These low results are substantially all on one animal, No. 22. In view of the fact that this animal made about the same gains of live weight as did the others (page 251), and in view of the seemingly erratic results of the nitrogen balances of 1919 the writer is inclined to interpret the Massachusetts results as indicating that a protein supply but slightly in excess of the total maintenance plus gain sufficed to secure nearly normal growth although insufficient to ensure maximum growth, *i. e.*, that the particular protein mixture used was nearly 100 per cent efficient. In view of the small number of results, however, this opinion is held only tentatively.

In the Virginia experiments the energy supply of the low-protein animals was 93 per cent of that of the high-protein animals in 1918 and 97 per cent in 1919. It would seem, therefore, that the smaller gains of protein by the former as compared with the latter or with the estimated normal must have been due chiefly to lack of protein.

Are the metabolism experiments representative?—A metabolism trial necessarily involves more or less disturbance of the regular daily routine and if the animal is not accustomed to such experimentation it may interfere with securing normal results. This would seem to have been the case especially in the Massachusetts experiments of 1919, as is noted in the account of those trials, while the figures of the remaining experiments do not suggest any such influence. In all such experimentation, however, the preliminary training of the animals is a matter of much importance. In the experience of the writer, mature cattle, especially if selected with reference to their quietness, may be quite readily trained for such experiments and at least show no obvious effects of it upon their metabolism. In the case of young animals the proper selection and the subsequent training may very well offer greater difficulty and cause greater disturbance in their condition. This is a point which must be taken into consideration in the planning of experiments of this sort.

Aside from the foregoing considerations, a metabolism trial can cover only a small fraction of an entire feeding period and the question may be raised as to how far one is justified in assuming that a metabolism trial conducted under proper conditions represents such a period.

As regards digestibility it may be regarded as pretty well established that, with similar rations not differing widely in amount, the age of the experimental animals is not an important factor, that the variations in the digestibility of the rations from time to time are not very great,[1] and that the differences observed may have sometimes arisen from too short periods for the collection of the feces. While there is a certain possibility of error, the writer believes it to be much less in carefully conducted experiments than the relatively large ones which may apparently be involved in the use of average digestion coefficients.

As regards the urinary nitrogen, we have little basis for comparison. We must either forego any determination of the actual gain or loss of protein by the animal or depend on making as frequent balance trials as practicable, conducting them with as little disturbance to the animal as possible.

Furthermore, it may be remarked that, barring a disturbance of the animal's metabolism by the experimental conditions, a metabolism trial shows the digestibility and rate of gain of protein at a particular date—a sort of instantaneous photograph of what is going on in the body—and the results may be compared with what we regard as normal for that species and age. If even two or three points on the curve of growth can thus be definitely fixed a comparison with the results of reasonably frequent weighings and measurements should give a pretty definite idea as to the efficiency of the rations. The writer is at present inclined to think that more frequent metabolism trials, if they can be conducted without undue disturbance of the experimental animals, is a hopeful line of approach to problems of this nature. For mature cattle on rather light rations he has found no difficulty in securing apparently normal results from continuous metabolism trials covering as much as 100 days. It may well be doubted, however, whether normal growth could be obtained under such conditions but more study of the technique of this sort of investigation seems very desirable.

Was the protein mixture identical?—The plan of the experiments contemplated the use of an identical mixture of proteins in all cases, the computation of the proportions of the four feeding stuffs necessary to secure this being based on their actual composition and on average digestibility. The actual digestibility of the total protein of the rations, however, was decidedly less than that computed and there is no means of determining whether or not this deficit of digestibility affected all the individual proteins proportionally. We can only assume that the differences, if any, were not sufficient to seriously vitiate the comparisons of the rations.

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[1] Compare "Nutrition of Farm Animals," page 602-3.

LIVE WEIGHTS AND MEASUREMENTS

The results of the weighings and measurements of the animals have been considered in the accounts of the individual experiments. Reference to these will show that in general the live weights confirm the conclusions drawn from the results of the metabolism experiments although on the whole making a rather more favorable showing for the low-protein rations as compared with the high-protein.

In comparing the gains in live weight it would appear that account should be taken of the differences in the initial weights of the animals, since obviously a gain of 50 pounds, *e. g.*, by an animal originally weighing 200 pounds is relatively greater than the same gain by one originally weighing 250 pounds. In other words, the smaller animal would double its weight more quickly. It would seem, therefore, that a fairer expression of the results would be obtained by expressing the gains as percentages of the initial weights of the animals. Table 46 summarizes both the actual and the percentage gains by all the animals, grouped in pairs as arranged by the experimenters. It appears from these results that the increase in live weight, both absolute and relative, by the low-protein animals was in every case except the Ohio experiments somewhat less than that made by the high-protein animals. Comparing the means of the several experiments, the increase by the low-protein animals was the following percentage of that made by the high-protein animals.

	On basis of absolute gains	On basis of relative gains
Massachusetts experiments of 1918	88%	88%
Virginia experiments of 1918	83%	71%
Ohio experiments of 1918	100%	105%
Massachusetts experiments of 1919	99%	93%
Virginia experiments of 1919	84%	79%

TABLE 46

Gains in live weight

	High-protein					Low-protein				
	Animal	Total gain	Percentage gain	Normal total gain	Normal percentage gain	Animal	Total gain	Percentage gain	Normal total gain	Normal percentage gain
	No.	Lbs.	Per cent	Lbs.	Per cent	No.	Lbs.	Per cent	Lbs.	Per cent
Massachusetts, 1918	269	176.0	75.2	170	51.4	270	136.0	67.3	173	68.1
	3	194.5	71.0	218	66.9	4	174.0	60.8	209	59.9
	5	181.5	69.8	209	59.9	6	161.5	61.2	209	59.9
	7	187.0	74.5	209	59.9	8	176.0	65.9	209	59.9
	Means	184.8	72.5	201.5	61.5	Means	161.9	63.5	200.0	61.5
Massachusetts, 1919	19	171.0	79.9	252	101.2	18	217.5	71.9	227	75.2
	21	228.5	80.5	252	101.2	20	226.5	78.5	239	86.6
	23	212.5	70.8	209	59.9	22	207.5	69.7	209	59.9
	25	221.0	67.7	178	43.7	24	170.0	56.7	178	43.7
	Means	208.3	74.1	222.8	71.1	Means	205.4	69.1	213.3	63.9
Ohio, 1918		141	41.0	124	39.2		141	43.0	124	39.2
Virginia, 1918	71	66.9	31.2	160	37.6	73	48.4	21.0	138	29.6
	72	56.6	29.7	160	37.6	74	53.8	22.4	138	29.6
	Means	61.8	30.5	160	37.6	Means	51.1	21.7	138	29.6
Virginia, 1919	1	132	27.5	97	26.3	3	86	17.7	97	26.3
	2	100	24.2	95	24.4	4	110	23.4	97	26.3
	Means	116	26.0	96	25.3	Means	98	20.5	97	26.3

Compared in either of these ways, the results are in favor of the high-protein rations, although not so markedly as those on the protein gains considered on pages 276-283.

The gains in live weight may also be compared with the normal gains for age as estimated from Eckles' results. This has been done in columns 4, 5, 9 and 10 of Table 46. It appears that the absolute gains in pounds by the high-protein animals were greater than the estimated normal for that age in six cases out of thirteen while with the low-protein animals the increases in weight were less than the estimated normal in every case but one.

If, however, account be taken of the differences in initial weight, and the comparison be made between the percentage gains it appears that the *relative* increase in weight by the high-protein animals was greater than the estimated normal in eight cases out of thirteen and that the same thing is true of the low-protein animals in six cases out of thirteen.

The question of special interest, of course, is whether the low-protein rations were adequate to support normal growth. A comparison of the means of Table 46 shows the increase by the low-protein animals to have been the following percentages of the estimated normal.

	On basis of absolute gains in pounds	On basis of gains per 100 initial weight
Massachusetts experiments of 1918	81%	103%
Virginia experiments of 1918	37%	48%
Ohio experiments 1918	114%	110%
Massachusetts experiments of 1919	96%	108%
Virginia experiments of 1919	101%	78%

In general it appears that the relative gain in weight by the low-protein animals was fully equal to the normal in the Massachusetts and Ohio experiments but distinctly below it in the Virginia experiments. This fact as regards the Massachusetts and Virginia experiments seems to correspond with the available protein supply in excess of maintenance as shown in Table 45 and already considered on pages 281-285.

On the whole, the live weight results make a distinctly more favorable showing for the low-protein rations than do the results of the metabolism experiments, although the advantage still appears to be slightly in favor of the high-protein rations, a fact which is perhaps explicable by their slightly greater energy content. The measurements of the animals in the Massachusetts experiments appear in general to confirm the live weight results.

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THE RESEARCH ACTIVITIES OF DEPARTMENTS OF THE STATE GOVERNMENT OF CALIFORNIA IN RELATION TO THE MOVEMENT FOR REORGANIZATION

Prepared for the Division of States Relations of the
National Research Council

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INTRODUCTION

This following report by Dr. James R. Douglas is the first contribution from a study of the status of science in state government which has been undertaken by the Division of States Relations of the National Research Council.

In this study the assistance has been enlisted of a number of men interested in the development and application of scientific knowledge in governmental agencies from the point of view of those who have made a particular study of theories of government, and also of men of science engaged in the administration of the scientific departments of various types of government. Without assuming responsibility for them, the Division of States Relations plans to publish from time to time reports which it is hoped will contribute to the discussion of the proper place and function of scientific research in state government.

As this study is continued, it is hoped to show the extent to which the scientific departments in state governments constitute a resource for research, and also whether the present organization, relationships, and contacts of these departments are such as permit the highest development and most effective application of scientific knowledge as used by this form of governmental agency. The departments which are primarily considered in this inquiry are the boards of health, boards of agriculture, conservation commissions, fish and game commissions, and the offices of the state geologist, state forester, state highway engineer, etc.

The need for exact knowledge in administration of public affairs has made the scientific departments of the states highly important parts of our governmental system. This examination of the organization and work of scientific agencies of the present government of California, as made by Dr. Douglas, is presented as constructive comment in the light of expert opinion upon the place of scientific research in state government. There may be difference of opinion as to the type or types of organization best suited to our needs. There can be no division on the question of desirability of a fuller understanding of the systems which we have thus far been able to develop.

JOHN C. MERRIAM, Chairman,
Division of States Relations,
National Research Council.

I. OBJECTS, METHODS, AND SCOPE OF THE SURVEY

This survey of the state executive and administrative departments in California was undertaken at the request of the Division of States Relations of the National Research Council, of Washington, D. C., and was conducted with two main purposes in view:

1. To ascertain to what extent scientific research has been made an active function of the various departments in the state government of California, and to learn the means available for the progressive application of scientific knowledge in the administration of these departments;

2. To learn what readjustments may be necessary to accomplish a better organization for scientific purposes. This latter purpose becomes a part of the whole question of the general reorganization of state government.

Three means have been employed in attempting to secure the information required to meet these purposes:

a. By examination of the laws of the state and the printed reports and other publications of the agencies in question. In this part of the work the writer of the report was greatly assisted by five of his graduate students organized as an informal seminar and serving without academic credit. Acknowledgements are made in this connection of the aid of Miss Alice E. Cook, Miss Josephine Hoyt, Miss Gertrude Roddy, Miss Helen M. Rocca, and Mr. H. G. Schutt.

b. By a questionnaire sent to the executive officer of each agency. This was accompanied by a letter of explanation amplifying what was desired and requesting co-operation with the National Research Council. Agencies which made replies were in the minority but included most of the more important departments. Most of the replies contained little more than the information appearing in annual reports. However, in a few cases, valuable additional information has been received. With one or two exceptions, a spirit of co-operation was displayed even where the object sought was misunderstood. One official, however, replied as follows, "I am not filling out the questions that you ask, because most of them are irrelevant, or I might say scientific . . . My opinion regarding commissions and bureaus is that they have too much scientific endeavor and not enough practical work; in other words, too much red tape. University men are responsible for much of this." This extract is given to indicate an attitude which is held by some, fortunately a very few, state officials, and which must be recognized as part of the problem of securing the extension of scientific standards to state government.

c. Through interviews with the executive or other important officers of the various agencies. Experience in regard to this method of approach has been that little in the way of supplementary detailed information may be expected, but in some cases valuable ideas and side lights upon the problem in general may be obtained to assist in arriving at a proper perspective. Here again, a spirit of co-operation was in evidence, even where doubt was expressed as to results which could be expected.

While enumerations and classifications vary to some extent, there are approximately 120 agencies comprised in the executive branch of the government of the state of California. In order fully to understand the situation of scientific research in the state departments there should be presented first an account of the composition, powers, duties, functions, internal organization, and relations with other agencies of those departments. Such a presentation is not possible within the limits of this report, and reference must be made to other sources for this information. The best available source is the report of the Governor's Committee on Economy and Efficiency of California, rendered March 12, 1919, which describes the state administration as it stood at the end of 1918. It does not include, however, the Department of Agriculture,—which in 1919 absorbed a number of previously independent agricultural agencies—the California Industrial Farm for Women, nor the State Board of Bar Examiners, all of which were created by the Legislature of 1919. It does include the State Irrigation Board, which in 1920 was declared unconstitutional. This report may be obtained from the Secretary of State at Sacramento.

On account of the nature of the present report a number of agencies have been omitted from the discussion for various reasons. One group has been eliminated because, while still appearing in the statute books and on the rosters, they are actually non-administrative in character or inoperative. Others perform functions of a special nature, often inconsequential in character. Examples of this type are the Commission to Investigate the Date of the Discovery of Gold in California, the Commission on Voting and Balloting Machines, the Tax Commission, and the Redwood Park Commission. Their existence is primarily due to the common legislative practice of creating a new agency whenever a new or special task is found to be done, instead of utilizing an existing agency fully capable of performing it. The practice may in part be due to the absence of any systematic and permanent scheme of administrative organization. In the case of special bodies for the investigation of current problems, it may be due to the non-existence of a legislative research department in the state government. Other groups eliminated from the present discussion are those dealing with the administration of public buildings and memorial properties, such as the Trustees of State Burial Grounds, the Guardian of Marshall's Monument, and the Superintendent of Capitol Buildings and Grounds; with institutional administration, such as state normal schools, homes, hospitals, and correctional schools; and with regional administration, such as boards of harbor commissioners, boards of pilot commissioners, and trustees of irrigation, reclamation, and sanitary districts. Due to the present extreme decentralization of administration, the agencies falling within the two latter groups form an almost independent field of administration, related to central organization only by means of very loose ties of supervision. From the point of view of organization these groups constitute very important units in the problem of state administration.

Further, certain very important groups of scientific agencies have been omitted from this discussion, though they really constitute a part of the state system as a whole. These include certain county agencies, the administrative functions of which are based upon scientific knowledge, and also important departments of city governments, especially those concerned with health and sanitation. There are also the highly specialized facilities of the state university and of other educational institutions of the state, the relations of which to the state government are so extensive and important as to warrant at some time a separate treatment. Another portion of the scientific resources of the state is contained in the scientific work carried on by other types of institutions in the state and by industrial corporations. These additional agencies have been omitted in this consideration largely on account of limitations of time available for the present study which has made it necessary to confine it to those departments which constitute a part of the central governmental system of the state.

The above groups of administrative agencies having been eliminated, the following list remained to be examined to fulfill the objects of this report:

Secretary of State
Controller
Treasurer
Attorney General
Surveyor General
Superintendent of State Printing
Adjutant General
Railroad Commission
Board of Accountancy
Board of Agriculture
Department of Agriculture
Banking Department
Board of Bar Examiners
Building and Loan Commission
Board of Charities and Corrections
Civil Service Commission

- Board of Control
- Corporation Department
- Bureau of Criminal Investigation and Identification
- Board of Dental Examiners
- Board of Education
  - Superintendent of Public Instruction
  - Assistant Superintendents of Public Instruction
- Board of Embalmers
- Department of Engineering
  - Highway Commission of the Department of Engineering
- Board of Equalization
- Board of Fish and Game Commissioners
- Board of Forestry
- Board of Health
- Historical Survey Commission
- Commission of Immigration and Housing
- Industrial Accident Commission
- Industrial Welfare Commission
- Commissioner of Insurance
- Bureau of Labor Statistics
- Land Settlement Board
- State Library
- State Market Director
- Board of Medical Examiners
- Mining Bureau
- Motor Vehicle Department
- Board of Optometry
- Advisory Pardon Board
- Board of Pharmacy.

It is recognized that this study might profitably have included a review of the history of the development of the government of California, a more extensive statistical summary of scientific work in progress or already accomplished, and a résumé of expenditures for equipment and operation in those departments which will be discussed, with some attempt to ascertain the approximate proportion of the state's appropriations which are applied to administration and to research, and with a statement as to the personnel at present enlisted, methods of selecting the scientific members of these departments, the basis of their compensation, their tenure of office, working conditions, etc. Here again the time available for this study has made necessary limiting it to its present scope.

II. SURVEY OF SELECTED STATE DEPARTMENTS

With the elimination of various state agencies in the list just given which obviously carry on no investigations whatever, the remaining agencies have been examined with a view to developing information pertinent to the purposes of this report.

After giving the term "research" the broadest possible meaning and including within the scope of that meaning every agency which performs any functions which can possibly be included within the term, there are twenty-eight agencies in California which are concerned in some way with scientific research or the systematic application of scientific knowledge.

Adopting a classification which is not altogether logical but which may serve in a measure to group and distinguish them, we may say that these twenty-eight agencies fall into the following categories. By no means is all of the work of many of the departments, as grouped in this provisional classification, of the type indicated by the heading under which a given department may be listed, but certain major parts of the work of these several departments are taken as mainly characteristic of them for the purpose of analysing the degree to which these departments are contributing new knowledge for the service of the state.

1. Testing.
2. Technical (the work of the agency being administrative but applied in such a systematic and specialized way as to be regarded as scientific).
3. Statistical.
4. Investigational (the work of research taking the form of studies or surveys based upon cases or groups of facts or the collection of data).
5. Research proper (the work consisting of a more purely scientific grade of research, including experimentation).

Assembling and summarizing the data concerning the agencies in question under the foregoing headings, we find the following:

1. SUMMARY OF RESEARCH ACTIVITY

a. Testing.

State Purchasing Department.—The executive of the department affiliates with the Purchasing Agents' Association of the State and the National Association of Purchasing Agents, and the department is in touch through its testing engineer with the National Society for Testing Materials.

State Department of Weights and Measures.—"Commercial research of the most practical character is constantly maintained. This department may be considered as an economic regulator for the consuming public in protecting them against commercial fraud and misconduct. All weights and measures problems wherein dimensions are concerned are referred to it. Intricate trade problems appertaining to the estimation of quantity are referred to it and have its attention." County sealers are instructed in their practical, scientific, mechanical, legal, and technical duties, are given practical demonstrations with measuring, weighing, and testing devices, and are examined as to their proficiency. At conferences of state weights and measures officials lectures on scientific subjects appertaining to weights and measures are provided. Work of educating the public by pamphlets, lectures, and educational exhibits at state fairs is undertaken.

State Highway Commission.—Under the headquarters Engineering Department there is the office of Geologist and under his direction the work of field geology and the testing laboratory in charge of the testing engineer. The work of the geological department has consisted in reconnaissance surveys for materials for highway construction. In the undeveloped sections of California the examination of materials consists in locating suitable deposits of rock, sand, and gravel, and estimating the quantities available. In the more developed sections of the state the reconnaissance survey for proposed highways usually consists in visiting the different producing companies, examining their equipment and available supplies, and reporting as to possible output and shipping facilities. The testing laboratory tests all samples of material proposed for use in highway construction. The testing laboratory also has made a series of tests on sections of the finished highway, giving information as to strength and wear-resisting qualities actually produced in the field. A number of special tests have been conducted in the laboratory to determine the effect on the highway construction materials when the highway is to be built in regions presenting unusual chemical, physical, or temperature conditions. The testing laboratory has made a large number of tests to determine the suitability of hitherto untried materials that have been suggested or recommended for the use of the Commission.

State Board of Harbor Commissioners.—Reports of this agency show that in connection with its department of Chief Engineer a testing laboratory is maintained. All construction materials, such as cement, structural and reinforcing steel, asphalt, etc., are tested and screen analyses are made of sand, gravel, and crushed rock for use in concrete. Samples of the concrete used in all construction work have been regularly tested.

b. Technical.

Railroad Commission.—While the Commission is primarily a quasi-judicial and administrative agency, most of its work is of a highly technical and scientific character. The collection of evidence, history, and facts pertaining to a case preliminary to rendering a decision involves elaborate and painstaking investigation. This work is done by the various experts of the staff.

Department of Engineering.—The research activities of the department are those incident to public works engineering.

State Board of Prison Directors.—The reports show that every person at the time of entrance to a state prison is given a thorough examination by a physician and a dentist, followed by an examination by an educational director; that no assignments to labor are made until the head physician reports the prisoner physically able to work; that drug addicts are placed under special treatment; that insane prisoners are transferred to state hospitals; and that prison treatment and occupational assignments aim at eventual rehabilitation of the individual.

c. Statistical.

State Board of Agriculture.—In accordance with the law requiring such a report, a statistical summary of the agricultural production and resources of California is made each year by the statistician of the Board.

Office of State Controller.—While primarily an administrative agency, the Controller suggests plans for the improvement and management of the public revenues. The annual statistics of counties and municipalities prepared by his office not only provide valuable data for the study of local administration but enable him through the prescription of uniform accounting forms to control in some measure the administration of local finances.

Bureau of Labor Statistics.—The Bureau gathers statistics relative to the number of employees and salaries paid by the various manufacturing industries together with statistics from the various labor unions covering hours of work and rates of pay. This information is incorporated in the regular biennial report together with other statistical data appertaining to the work of the free public employment bureaus under the supervision of the Bureau.

State Board of Education.—"The work of this office is largely administrative and supervisory. In spite of the fact that we have been desirous of obtaining funds for thorough scientific investigations into matters educational, we have not been able to secure sufficient appropriations for the purpose. I am hoping especially to develop a bureau of educational research in connection with the office. This bureau of educational research will have charge of investigations into age and schooling records, problems of retardation and elimination from school, scientific analysis of school statistics, etc. At present our statistician performs these functions in a most rudimentary way. It seems to me that our educational administration must be put upon a more scientific basis if we are to obtain results more nearly commensurate with the great outlay for public education." (Statement of Superintendent of Public Instruction.)

d. Investigational.

State Board of Control.—The law provides that the Board of Control shall have general power of supervision over all matters concerning the financial and business policies of the state. The duties of the Board cover the audit of all state expenditures, including the pre-audit of all institutional and departmental expenditures, and, organized with the State Controller at the present time as an informal Budget Board, the preparation of a budget of the necessary expenditures and the revenues for meeting them.

The State Board of Control directly performs no functions of a scientific research character, unless it be that the budget is prepared "along scientific lines with due regard to the comparative necessities of the different institutions and departments," and that systems of accounts are devised by it. By its sympathetic or non-sympathetic attitude, however, the Board can largely determine the extent to which scientific application is made in the administration of the state institutions. Under the Board's supervision, studies of the occupational exercises of defectives, especially at the Whittier State School, experiments with the dietaries in state institutions by a nutrition expert from the University of California, and scientific studies in penology at the state prisons, have been made.

State Board of Equalization.—The Board reports that it conducts investigations of the tax systems of other states and countries and the systems for the disbursement of their public funds, principally through the collection of laws and reports.

State Water Commission.—The work of the Commission is principally administrative, investigational work being handled on a cooperative basis with the U. S. Geological Survey, U. S. Department of Agriculture, State Engineer, etc. Occasionally water resource investigations are made by the Commission involving surface and underground waters, the most important to date being the ground water and percolation investigations carried on at Niles Cone on Alameda Creek. This is the most extensive investigation of its kind ever conducted. Such investigations as are carried on by the Commission are performed by its Hydraulic Engineering staff for application to specific problems in the administrative functions of the Commission. Looking to the future, the Commission has in mind the comprehensive assembling of existing water resource investigations, both surface and underground.

State Mining Bureau.—This Bureau reports on proposals to drill oil wells, on tests of water shut-off in oil wells, on drilling and deepening of oil wells, on abandoned wells, on proved acreage, and on the number of producing oil wells. These reports are based upon logs filed with the Bureau. A graphic log shows at a glance all the mechanical and geological details recorded in the written log and makes it possible readily to compare underground conditions at a number of wells. Peg models are constructed and placed on exhibition at the various offices. These models show clearly most of the underground conditions of a locality and are one of the most useful features of the work of the department. About one-half of the proved acreage of the state has now been covered by models.

State Board of Forestry.—Although the State Forester reports "No research" on the questionnaire, official publications mention examination of causes of all fires throughout the state, whether inside or outside national forests, and studies of the proper trees to plant in different sections of the country with reference to soil and climatic conditions and purposes to be served.

Industrial Accident Commission.—"Such research work as is carried on is done mainly in the safety department and medical department, but with the co-operation, to a limited extent, of the scientific departments of the State University and the two great medical colleges of the state, the University of California and Stanford. Such research is generally carried on by the organization to which an appeal is made, the Commission itself doing very little of the original research work, but acting through trained men who avail themselves of any assistance they can get."

The Department of Rehabilitation in 1918 began a survey of all the serious permanent injuries that had occurred in the state during the preceding four years. The results of this survey were published in 1919. The Commission publishes each year a statistical report covering various subjects dealing with industrial injuries and their consequences. The Department of Safety publishes the "California Safety News," containing articles by the safety engineers and inspectors and by experts not connected with the department.

Commission of Immigration and Housing.—Investigations into the living conditions, housing, labor, domestic relations, business, etc., of immigrants as well as into methods of educating them are constantly carried on by the Commission through its various departments. The methods of conducting these investigations are by case examinations, surveys, individual inspections, institutes, and studies by specially appointed committees. A very large amount of field work is done by the Commission. The field of work is so large and hitherto so imperfectly explored that the methods of experimentation and research have become standardized in only a small degree.

Industrial Welfare Commission.—The Commission is concerned with the investigation of wages and conditions of labor. "Conferences are held with persons not directly connected with a particular industry, as economists, experts, and social and civic agencies, so that the theoretical as well as the practical problems may be given consideration."

State Library.—The State Library conducts studies in comparative legislation on subjects before the legislature or under investigation by state departments, the compilation of state laws relating to activities of state departments, the preparation of reading lists on questions to be voted on by the people, and investigations in California history.

State Commission in Lunacy.—This Commission conducts the collection of statistics based on psychological tests of inmates of state institutions, studies of most of the diseases connected with feeble-mindedness or insanity, tests of blood serums—a local agent making Wasserman examinations for such hospitals as do not have laboratories of their own—surgical work, and studies of the dietaries of state hospitals. Examinations are made, usually with the patients before the whole medical staff of the hospital, at which time reports on all laboratory examinations and various tests are made, and the results recorded. Reports of investigations are made to the hospital staff, and the after-care of the patient is based largely upon the information so obtained.

State Board of Charities and Corrections.—The following studies and surveys have been conducted under the auspices of the Board: survey of mental deviation in prisons, public schools, and orphanages; state-wide survey of the effect of the war on social agencies, a directory of social agencies, a study of dismissals from ten children's institutions, study of child-placing agencies, standard dietary for an orphanage, survey of industrial day nurseries of California, study of the probation work in six counties, nutritional survey of twenty-two institutions for children, investigations among mothers in Fresno working in the raisin and fig industry, bulletin on "County Out-Relief in California," county surveys, dietary for aged people in almshouses, state wide study of jail conditions in California, study of the influenza in state institutions, statistics as to alcoholics and drug addicts in state hospitals, and surveys of the educational systems and methods for punishment in the three state schools.

These studies are made by agents and by Board members, personal case work, visits to institutions, and the questionnaire method as the study demands. Publicity is of two kinds—by published bulletins and by facts given to the press. Studies are made for the practical purpose of remedying conditions. Where the Board has direct jurisdiction, the results are applied directly. Where the Board has supervision, the findings are referred to the proper authorities for action.

State Bureau of Criminal Identification and Investigation.—"Owing to the tremendous volume of work and lack of help, no intensive research work is possible. A system was devised for the identification of criminals by their method of operation and this has proven highly satisfactory. In the first report of the Bureau, for the period ending June 30, 1918, the board of managers recommended that an expert in handwriting, chemical analysis, and microscopy be employed and attached to the Bureau for scientific investigation and research."

State Civil Service Commission.—"Investigations are continually being made into the results of examinations, for the purpose of ascertaining, so far as possible, what tests determine most accurately the elements of fitness which they are designed to reveal. Co-efficients of correlation have been completed by the Pearson method and graphic charts have been prepared to aid in the determination of the suitability of tests. Some follow-up work has been carried on to discover whether or not practice confirms the conclusions of investigations. The work along this line has not been very extended because of the time limitations of the staff. This Commission is earnestly recommending the combination of all civil service commissions for the establishment of a central bureau of research. The functions of this bureau would be to carry on scientific investigations into the adequacy of civil service examinations and tests and to devise new examinations and tests."

e. Research Proper.

State Department of Agriculture.—The research work of this Department has consisted in the collection of beneficial insects, investigation of causes of plant disease, investigations to increase the productivity of Zanti Corinth grapes by girdling, experimentation with herbaceous grafting of grapes, investigation to overcome coulure of Muscat grapes, plant pest surveys, testing of dairy cows, chemical examination of commercial fertilizers, insecticides, and fungicides, standardization of milk testing apparatus, testing of dairy products, control of infectious diseases of live stock, inspection of plant products for plant pests.

State Board of Fish and Game Commissioners.—The Commission has carried on experiments in hatching and rearing fish to determine the effect of a change in the habitat of fish, experiments in breeding of game birds in captivity at the State Game Farm, scientific investigation of the fisheries to develop fisheries conservation work; collection of materials for scientific purposes, field investigations of game refuges, a study of food of ducks and of other non-game birds, study of damage to rice by ducks and blackbirds, study of the beaver in California, study of attempts to acclimatize foreign birds, census of the pronghorned antelope, notes on the life history and habits of game birds and mammals from reports of deputies added to files, studies of water resources of the state to aid in determining upon intelligent protective and preservative methods for fish and game, data being collected relative to streams, lakes, etc., and maps prepared. The gathering of statistics and compiling of data is believed to be the most important function. The best statistics of food fishes obtainable for the state are produced by the Commercial Fisheries Department of the Commission.

California Historical Survey Commission.—This commission makes surveys of the material on local history within the state, by investigating documents in local depositories, in the possession of private individuals, and from other sources of original information on the early history of the state, and compiles and keeps a record of such information. It also studies the architecture of the several missions and makes models thereof and prepares plans and specifications for use in the restoration of the missions.

State Board of Health.—The Board of Health has carried on experiments with chemical means of disinfection of drinking cups, biological examinations in the diagnostic laboratory for seventeen diseases, a study of standardization for tuberculosis wards of county hospitals, surveys in Orange, Alameda, and Sonoma counties showing causes contributing to tuberculosis, surveys in Los Angeles and San Francisco among operative employees in motion picture theatres, surveys, reports, and tests of sewage treatment plants and polluted streams, inspection and tests of swimming pools, special investigations, such as sanitary surveys, garbage inspections, and piggery inspections, sanitary inspection of food selling and food producing shops, and of food in state institutions, compilation of vital statistics, reduction of malaria through eradication of mosquitoes, campaign for sanitation in mines to lessen hookworm disease, reduction of typhoid fever and similar diseases through efforts of the Bureau of Sanitary Engineering in locating sources, preparation and distribution of vaccines, tests and treatment in cases of venereal diseases.

Correctional Schools.—A Department of Clinical Diagnosis at the Whittier State School conducts research into the causes and consequences of delinquency and mental deficiency, and inquires into social, educational, and psychological problems relating thereto. It also publishes the "Journal of Delinquency," a publication devoted to the scientific study of problems relating to social conduct.

2. PRESENT CONDITIONS SURROUNDING RESEARCH IN STATE DEPARTMENTS

On the whole this summary cannot be said to show a very considerable development for the subject of research among the great number and variety of agencies in the administration of a state which in recent years has entered so many diverse fields of governmental activity. The reasons for this are various:

a. As seems inevitably the case in all public business, the tendency seems always to be towards the routine. After the initial exploration of the field of activity, often made by a special commission of investigation, the agency tends to settle down to the performance of a regular round of functions and the longer it exists the less the attempt is made to discover new fields of usefulness or to perfect methods of governing the old. Even less are the efforts made to profit by the ~~experiences or studies of others in the field~~. Seldom is any thought given to seizing opportunities which present themselves during the course of operation for discovering and presenting to the world "knowledge for its own sake." It is only when the agency happens to fall under the direction of the exceptional man or group of men or when proper pressure comes from above that much is done in the way of "research," a term which covers all these things.

b. The whole organization of the state administration is of such a character as to discourage the function of research. By this is meant: (1) the diffusion of activities among so large a number of bodies, often overlapping in their functions; (2) the absence of any superior co-ordinative and directive authority which might intelligently promote the objects of research; (3) the inevitable emphasis upon politics rather than expertness in administration which is incident to such a plan of organization—the executive position being insufficiently conspicuous and remunerative to appeal to any but the professional politician who is not apt to have a deep-seated reverance for science or research; (4) the "shallowness" of the internal organization of departments which results from the diffused plan of general organization, except in a few cases each agency being assigned such a small portion of the whole business of the state that the force of its personnel is necessarily limited, there are practically no intervening positions between the routine employees and the executive of the agency (who, even though he may have had scientific training and is conscious of the value of research work, is prevented from giving his attention to it by the press of administrative duties) and there is little chance for the existence of a separate subdivision charged with the function of investigation.

c. It is often difficult at present for administrators who are really concerned over the necessity for research to secure encouragement and financial support for its activities. It even seems to be a difficult deductive process for the ordinary legislator and sometimes for the budgetary officer to perceive that frequently even a modest investment for study and investigation will produce an excess of profit in the form of service to the state or economies to its treasury. This attitude of the popular representatives is in large measure but a reflection of popular sentiment. Two examples are given in the data of the difficulties experienced by conscientious administrators on account of the indifference or distrust of the lay mind of research activities. "In spite of the fact that we have been desirous of obtaining funds for thorough scientific investigations into matters educational," says the State Superintendent of Public Instruction, "we have been unable to secure sufficient appropriations for the purpose. I am hoping especially to develop a bureau of educational research in connection with the office. . . . It seems to me that our educational administration must be put upon a more scientific basis if we are to obtain results more nearly commensurate with the great outlay for public education." The State Civil Service Commission, in reporting its research activities, explains that "the work along this line has not been very extended because of the time limitations of the staff." The staff is very limited and must give most of its time to routine duties, although the Commission is aware that scientific re-examination of its work would be extremely valuable, and it would welcome adequate support for its research work.

One of the causes which is largely responsible for failure to develop research as the basis for administration in government is undoubtedly the lack of appreciation on the part of the public of the vast importance of an extensive and growing basis of scientific knowledge in the business of public administration. The generous appropriation of public funds to general educational purposes is, however, indicative of response which may be expected from a more extensive understanding of the importance of research as a proper function of certain governmental agencies. The increasing public realization of the value of research is already shown in conspicuous examples which might be named in some state and municipal governments and particularly in the bureaus of federal government and in the large research establishments in many industrial corporations. With the further education of the public in the importance of research there is hope that this deficiency, where it exists in governmental agencies, can be corrected.

But, if the foregoing diagnosis is free from error, it must be clear that the infirm condition of research in state government is also caused by the faulty structure of the organism and that the first remedy lies in the reconstruction of the whole body. The problem of instituting research and the systematic application of scientific knowledge upon a sound basis is unquestionably bound up in the general problem of administrative reorganization. The following summary attempts to disclose the elements of this difficult problem and to describe efforts that have been made in California to solve it.

III. THE PROBLEM OF STATE ORGANIZATION

The status of research as a proper function of certain departments of a state government is very closely related to the general system of state organization. Any movement for reorganization or consolidation of state government cannot but effect the activity of the scientific deparments and ought to be calculated to increase the efficiency. For this reason any study of the research functions of state departments is fundamentally concerned with the general organization of the state and particularly with the organization and relationships of these scientific departments.

1. PRESENT SYSTEM IN CALIFORNIA

The state administration of California consists of a great collection of dissimilar agencies guided by no central directive authority and without cognate relationships with one another.

The Governor, nominally the "chief executive" and head of administration, is in fact without adequate means of exerting the authority which these terms imply. Nominally the Governor is responsible for the administration but he does not possess the essential attribute of the **authority** which must be coincident with **responsibility** to complete the scope of executive competence. Authority in government consists in the power, emanating from the chief executive and extending down through the various stages of an administrative hierarchy to the humblest departmental functionary, to appoint and dismiss at will.

The Governor of California possesses no such authority. Eleven of the most fundamental offices and agencies are constitutional bodies finding their source of authority in the same fundamental law from which the Governor derives his own competence. This places them at the same time beyond the bounds of legislative regulation. Seven of these offices, comprising practically all of the older and "regular" officers of the government, are elective and hence beyond the control of the Governor. These are:

Attorney General
Secretary of State
Controller
Treasurer
Board of Equalization (the four elective members)
Surveyor General
Superintendent of Public Instruction.

The remaining four, while constitutional bodies, are appointive by the Governor, but for the reasons given are placed beyond the reach of his full authority:

Railroad Commission (appointed for six years, the terms thus extending beyond the period of gubernatorial tenure, and removable only by joint address of the houses of the Legislature, passed in each case by a two-thirds vote).

Regents of the University of California (partly ex-officio, partly appointive for terms of sixteen years, practically beyond the scope of executive authority).

State Board of Education (the members are appointed for four year terms but in rotation so that no one Governor can completely reconstitute the Board).

State Board of Prison Directors (the members serve for ten years, thus serving beyond the Governor's term, and may be removed only after a hearing on grounds of misconduct, incompetency, or neglect of duty, offences which are very difficult of conclusive proof).

Another group of agencies, of statutory origin, are constituted wholly or partly of ex-officio membership. Some of these agencies are not so important, some are made up partly of the Governor or his appointees, but some are part of the fundamental machinery of the state and are composed entirely or largely of members not responsible to the Governor. In either case they add to the confusion of the situation.

Even where the members of agencies are dependent in the first instance upon the Governor's appointment, various factors restrict his complete control. In a number of cases their terms are overlapping and some of them serve during part or all of the Governor's administration without being subjected to his nomination. In some cases his nomination is subject to legislative confirmation. Unlike the well-established prerogative of the national executive, the state governor's power of appointment does not include as an incident thereto the power to remove, and frequently a different method of removal is provided by law. It is only in the case of officers who are appointed by and serve at the pleasure of the Governor that he has the requisite authority to take effective action when it may become necessary for the maintenance of efficiency and the enforcement of policy.

But even were the Governor endowed with the power which comes from complete control of policy-making personnel, this alone would not constitute him an effective director and co-ordinator of administration. The mere concentration of authority and responsibility in the hands of a single individual would create a burden too great for any individual to bear. An executive must act to a large extent through delegated authority and it is only where there is a hierarchy of subdivided labor and responsibility heading up in a group of chief administrators small enough to act with and for the chief executive in the exercise of control and to furnish him with adequate counsel and advice that effective centralization and co-ordination can be obtained. Such an organization effects a "departmentalization" of state administration, usually along functional lines, and results in the grouping together of similar functions under a common direction, the proper subordination of related functions, and the elimination of duplication in functions, equipment, and personnel. It results, too, in the standardization of departmental organization, the systematization of relationships between departments, and the creation of staffs large enough to include within each major department such service functions as, for instance, that of a division of research.

There is considerable duplication of effort in the administration of the state. In the activities which may be grouped under the heading of public works functions, are to be found parallel engineering organizations carrying on work which could better be done under central control. Similar conditions exist among the financial agencies and are particularly striking among those listed as performing the labor functions of the state. The seven normal schools of the state are conducted under seven local boards, allowing widely divergent policies to prevail where there should be a uniform state policy. The same is true of the state hospitals and the correctional institutions. An example of incongruity is the administration of the Orphans' Aid Act by the Children's Department of the State Board of Control, a function which should logically fall to the State Board of Charities and Corrections. No attempt is here made to give a complete enumeration of such discrepancies.

There exists a variety of forms of organization among the agencies of administration and little attention has been given to the adaptation of the form of organization to the function to be performed. The science of administration recognizes three pure types of administrative organization: the *bureau,* the *commission,* and the *board.* (1) The *bureau* is the most economical and most efficient from the point of view of administration. It is controlled by a single appointive head who, while he relies on the advice and initiative of his subordinates, is alone responsible for the conduct of his office. Its strong points are economy, definite fixing of responsibility, and power of swift action. (2) The *commission* embodies the principle of the collegiate executive, usually consisting of from three to seven members who jointly administer the affairs of the office. Commissions are difficult to subject to superior control, they tend to become irresponsible, and frequently their business is distributed piece-meal among the members, in which case they lose their collegiate character and the organization becomes hydra-headed. The employment of the commission type is really justifiable only where a quasi-legislative or quasi-judicial function or the administration of a public trust is to be performed. (3) The *board* embodies the principle of the "controlled executive." As distinguished from a commission, authority and responsibility are not vested in a collegiate body of paid officials actually performing the work of the office but in a group of laymen of a representative character usually serving without compensation and out of public spirit. The board itself does not administer either as a body or through committees but chooses an executive officer, presumably an expert, salaried, who gives his entire time to the functions of the board, having complete charge of all the details of administration. The board sits in judgment on the plans and conduct of the executive expert with the right to remove him for any reason it deems fit. During the time he continues to possess the confidence of the board, the executive officer usually exercises a large degree of authority and discretion. The board type contains certain elements of strength. It associates the layman and the expert in administration and brings to the service of the state the talents of able citizens. There is danger in the plan, however, from a disposition of board members to engage in politics. There is, also, frequently a tendency to take administrative duties out of the hands of the executive officer and to distribute them among the members of the board. This type of organization is open to the same objections that lie against the commission type in that responsibility is diffused, making superior supervision difficult and defeating the unity of administration. The modern tendency is away from the commission and board type and in the direction of the bureau type of administration. In fact, this is one of the essential features of the "departmental" plan of state administration.

The great growth of state administrative agencies in recent years has been characterized by the multiplication of boards and commissions, and in the matter of this kind of development California is in no way exceptional. While all three of the above types exist there has been an unwarranted use of the plural types of departmental executive in preference to the much more effective bureau type. Furthermore, there has been no careful observance of the purity of these forms, a description of which it has been thought advisable to give for this reason. There are boards which are called commissions and commissions which are called boards, there are boards in which the proper relationship between the lay members and the expert executive has been entirely abandoned, there are even "boards of commissioners." Perhaps the most flagrant violation of scientific principles of organization occurs in those boards where the executive officer, who should properly be the servant of the board, is made a member of the board and sometimes its presiding officer, thus occupying the unique position of being his own superior. This situation exists in the organization of the Commission in Lunacy, where the General Superintendent of State Hospitals, the executive officer of the Commission (which is really a board), is one of its members, this situation being complicated by the fact that all the other members are ex officio officers of the state administration and can by no process of interpretation be construed as "lay members." Turning to the organization of the Department of Engineering, we find an even more complicated situation. One of the members of its Advisory Board, which represents the board type of organization, is the same General Superintendent of State Hospitals referred to above as being at once a member and a subordinate of another state department; another is the State Engineer, who is also the executive officer of the board; another is the Chairman of the State Board of Harbor Commissioners (of San Francisco), a unit simply of regional administration; the Governor is chairman ex officio, and the other members are the three members of the California Highway Commission, which is in fact a subsidiary division of the Department of Engineering itself. In the organization of the State Board of Education, the situation is analogous by reason of the fact that the Superintendent of Public Instruction, the Secretary and Executive Officer of the Board, is not appointed by the board nor even by the Governor, for he is a constitutional officer and is responsible to no one but the people of the state who elect him, thus deriving his authority from no less a source than does the Governor himself.

It will be noticed that in two of the instances given above of unscientific board organization, the agencies concerned are composed entirely of ex officio membership. There are a large number of such ex officio boards and commissions in the state administration of California, as has been previously mentioned, and this fact detracts still further from its simplicity of organization. Aside from its violation of the representative principle which should govern in the composition of the board type, the use of ex officio membership is to be decried from other points of view. It is presumably justified on the ground of economy—that public officials have less business than they can profitably perform—and on the ground that where two or more agencies are performing related functions, correlation of activities can be secured by ex officio representation of each. Where the Governor himself is made an ex officio member, the presumption is that in this way he will be given some control over administration. None of these grounds constitute reasonable justification for the use of ex officio membership. It is not, or should not be, true that a state officer has more time than necessary at his disposal. If it is true, it is fair indication that his agency is not important enough to continue as an independent unit but should be consolidated with some other agency of related function. Where correlation between agencies is desirable, it can better be secured by means of a general superior advisory council of chief executives of departments who together form a governor's cabinet, as is contemplated under the "departmental" scheme. The business of an agency to which a state officer is assigned as ex officio member is to a considerable extent unrelated to that officer's main interests and duties and it is unreasonable to suppose that he will give his best efforts to it. It is a fact that the ex officio members of departmental organizations are seldom present at their deliberations and that these bodies are therefore deprived of adequate counsel. Where the Governor is an ex officio member he is apt to be placed in a false position. He should have a superior authority over decisions, not a share in their formulation in which a vote against him is apt to impair his prestige. The general use of ex officio membership is a practice to be avoided in the organization of state administration and should be confined to those few cases where the necessity for correlation of departments is imperative and cannot be effected in any other way. Such a necessity should scarcely ever arise in the "departmentalized" form of organization. The employment of the ex officio body in California is especially unfortunate because in most cases the ex officio members are those state officers whose positions are based upon constitutional origin and whose presence on so many boards and commissions adds still further to the disorganization and lack of definite responsibility.

Not only the general plan of organization of departments but also the internal distribution of their functions is important in state administration. Departments should be large enough so that a well-defined distribution of business becomes possible. They should be organized on a functional rather than on a personal basis. Clear distinction should exist between executive, routine administrative, and special or technical functions—as for instance, that of research. As a matter of fact, the existence of research units in departments will only become possible when the above conditions have been met. With due allowance for the differences which must occur on account of diversity of functions, a similarity of internal organization should exist throughout all branches of the state administration for reasons of simplicity, uniformity, clarity as to nature of duties performed, effective superior control, and standardization in such matters as positions of employment under civil service. The greatest diversity of internal organization appears in the departments of administration in California. In many of the agencies there is practically no formal structure, the office consisting simply of the chief officer, a deputy or two, and a small force of clerks and stenographers. In others, such differentiation as exists is placed entirely upon a personal basis, as, for instance, in the State Board of Charities and Corrections where the organization is surprisingly small in comparison with the importance of the duties performed. Here the office organization consists of: "1. The Institution Agent, 2. The County Agent, 3. The Chief Children's Agent and Children's Agents, and 4. The Statistician, who aids the Research Committee of the Board." In only a few departments are to be found well-knit schemes of internal organization founded upon a differentiation of duties, notably in the Department of Agriculture, the Department of Engineering, the State Board of Health, and one or two others

A final matter of consideration is the effect which the present state of organization has and which a proper plan of reorganization would have upon the whole personnel of state administration. The "shallowness" of most of the departments in the matter of personnel and the resulting lack of attention which can be given to research activities has already been referred to. The same lack of depth is responsible for the difficulty of standardizing positions of employment in the civil service of the state, a difficulty which is admitted by the officers of the State Civil Service Commission. Insufficiency of salaries hampers the attraction of trained personnel to the service of the state. Limited spheres of authority, the very doubtful prestige which attaches to the holding of public office as at present constituted, and the large degree to which scientific standards must give way to considerations of political expediency are responsible for the difficulty of enlisting in the higher reaches of the service men to whom even the meagerness of compensation would not be an altogether prohibitive factor. The relation of these things both to general efficiency of administration and scientific application and research is obvious. Only by economies which will come from consolidation, the avoidance of duplication, and the elimination of waste will it be possible to secure a rank-and-file personnel capable of performing scientific duties, and only by the setting up of large spheres of authority free from petty political interferences will it be possible to attract to their direction leaders and executives with the ability and breadth of vision capable of bringing about the realization of scientific standards.

2. MOVEMENT FOR REORGANIZATION IN CALIFORNIA

For a number of years governors of California have foreseen the need for improvement in the administrative machinery of the state.

Governor Henry T. Gage in his inaugural address of January 4, 1899, gave warning of the need for reform:

> The great extent of our state, its wonderful resources, the number of official departments, have hitherto afforded opportunity for waste and prodigality in the conduct of government. Among other things, we suffer much from over-legislation. *Already we have too many state boards and commissions* with extensive lists of subordinate employees. . . . This should be corrected.

Governor James N. Gillett in his inaugural of January 9, 1907, took occasion to address the legislature as follows:

> Our expenses appear to be increasing out of proportion to our increase in population and wealth. *We have many commissions to support, some which seem to me to be needless.* There is no denying the fact that California is one of the most expensive states in the Union to care for, and while our attention for years has been called to the fact, we still continue along the old way.

It is perhaps enough to say that in spite of these pronouncements, the state has continued practically "along the old way" to the present time.

An upheaval in the state's affairs came in 1911 when Hiram W. Johnson succeeded to the governorship. It must be remembered that Governor Johnson's program was one primarily of political reform. His purpose was to make the government of the state responsive to the people alone and while in addition to altering the machinery of the government to this end he succeeded in creating agencies for the satisfaction of social and industrial needs, these only added to the complication of the administrative organization. One measure in which he was interested was the "short ballot" and his recommendations in this direction in his inaugural address in 1911 suggested that the Clerk of the Supreme Court, the State Printer, the Surveyor General, the Superintendent of Public Instruction, the State Treasurer, the Secretary of State, and the Attorney General be made appointive. Such a plan would have greatly simplified the elective processes and would have centralized power in the hands of the Governor but it would have meant little improvement in the administrative situation from the point of view of organization. Governor Johnson's recommendations involved, it can be seen, several amendments to the Constitution. It is not surprising, therefore, that the only result was the making of the Clerk of the Supreme Court, not really an administrative officer, and the State Printer, both of them non-constitutional officials, appointive rather than elective.

Governor Johnson's recommendations contained the further suggestion that the appointive officials might be made into a Governor's cabinet. This suggestion, elaborated in his first biennial message of 1913, was accompanied by the additional proposal that the various hospital boards be centralized in a Board of Administration, and that like central boards be established for state units dealing with education and with health. He also advocated, among other readjustments, that the various attorneys for commissions and boards be placed under the jurisdiction of the Attorney General. These proposals did not meet with success, perhaps due to the fact that the Governor did not urge them upon the legislature with the same vigor as he did other policies in which he was more interested. A bill creating the Board of Administration never progressed beyond the lower house of the legislature.

Governor William D. Stephens succeeded Governor Johnson, apparently determined upon a policy of economy. In a special message to the Legislature of 1917, he said:

> If . . . you are able without impairment of the present efficiency or value of any department—*by consolidation or administrative simplification*—to reduce the cost of government such course would no doubt meet the approval of our people.

On November 25, 1918, Governor Stephens took a more positive step by appointing, on his own initiative, a Committee on Efficiency and Economy to make a thorough survey of the activities of the state government, "with a view to formulating a definite plan for improving the administration of the state's affairs and for introducing such economies as are possible without prejudice to the public welfare or without impairment of present efficiency."

In his first biennial message to the Legislature of 1919, the Governor, in notifying the members of the appointment of his Committee on Efficiency and Economy, said:

> Recognizing that the people should have an exact knowledge of what they get for every dollar spent for governmental purposes, I have caused a survey of our various administrative boards and commissions to be made by a committee of citizens and officials. This committee will make a critical examination of the powers, duties and internal organization of all boards and commissions, and will ascertain to what extent their powers and duties may overlap and what economies may be effected without impairing the quality of the service.
>
> Without anticipating the report of the committee *I am convinced that economies can be effected through the better organization and co-ordination of these great administrative agencies.* . . . The government of California has been reconstructed in the last few years, during which time, we have experienced a development along social, humanitarian, and industrial lines which surpasses the achievement of any other state. Exactly the same results, however, follow in governmental development as follow expansion in private business; and as in private business, after

> growth and development, we now must remove all extraneous and unnecessary expense and practice the strictest economy in carrying on the state's activities. . . . If there be debris and structural staging, necessary to the work of building, but unnecessary and expensive to proper maintenance, such nonessentials must be removed.
>
> On the other hand I have no sympathy whatever with the cry for a reduction of expenditures to a point which would destroy the highly beneficial service now rendered to the people of the state. . . .
>
> The problem which confronts us is this: The people of California have demanded that their government shall render services and perform certain work. Those services and that work are being performed. The people have a right, as well, to expect and demand that the costs be kept at the lowest point consistent with good service. That demand is wholly reasonable, and it is our business to see to it that the wish of the people . . . is carried into effect.

With these clear expressions of executive intention to guide them, the committee of eleven members, including several state officers and legislators, serving without funds, associated with themselves persons throughout the state recognized for their ability and familiarity with the problems to be studied, and by means of direct communication with all state agencies and hearings to which both officials and interested citizens were invited, as well as by individual research on the part of the members, collected within a comparatively short time a large amount of data upon which they based their recommendations.

3. REPORT OF THE COMMITTEE ON EFFICIENCY AND ECONOMY

The Committee rendered its report to the Governor on March 12, 1919, when the time of the legislative session was already more than half spent. Owing to the time limitation placed upon its work, the Committee had not been able to make recommendations for changes other than those which could be put into effect immediately by legislative enactment. Apparently, too, the Committee was moved by considerations of political expediency to the extent of believing that if it made its report rest upon scientific principles alone it would excite such bitter political opposition as to insure the complete defeat of the report. Therefore, the report suffers from lack of completeness in that it excepts from its recommendations a number of important agencies. Nevertheless it constitutes a valuable survey of the state administration and its recommendations if adopted would undoubtedly effect a noticeable improvement in efficiency. As to the possible economies of the changes recommended, the Committee estimated that they would amount to approximately $550,000 per biennial period.

The Committee adopted as its guiding principles three of the propositions which have been discussed above as essential to efficient public administration. These are:

1. Centralization of responsibility.

2. Co-operation of the larger organization units.

3. Co-ordination of agencies which perform similar or allied functions.

"The co-ordination of agencies with allied functions in comprehensive departments," said the report, "will do away with overlapping of duties and duplication of effort, and will lessen the number of units to be supervised, thereby making review more adequate and supervision more real. There are no factors which are greater causes of inefficiency than decentralized control and inadequate supervision and review."

In applying these principles the Committee directed its investigation primarily to the group of administrative agencies for which the Governor is theoretically responsible. In this group, comprising one hundred departments, boards, and commissions, it found that "many perform functions closely allied and there are, in many instances, duplication and overlapping of effort. There are many groups whose work is similar but independent in operation, which, if co-ordinated and centralized under one executive head would make for more efficient and economical management."

To remedy these conditions, the Committee determined to embody its guiding principles in a plan of reorganization by:

1. The creation of a Governor's cabinet, composed of departmental executives appointed by him. "The centering of larger responsibilities in departmental executives should be accompanied by the creation of a Governor's cabinet, composed of those executives. Such a cabinet should assist the Governor in administering the affairs of the state and in formulating state policies. The direct effect of a cabinet so organized would be closer co-operation between departments, increased efficiency in administration, and better service to the public."

2. Insuring co-operation of various departments by bringing their administrative officers together in an executive council.

3. Placing in departments, under one executive head, those agencies which perform similar or allied functions.

In addition to leaving untouched all those offices filled by election by the people, the Committee found it impracticable "because of the great diversity in the nature of the state's activities," to correlate all of them into larger administrative functions. For this reason the following departments were left to function independently:

1. The group of examining boards dealing with professional standards, it being seriously questionable, in the opinion of the Committee, whether increased efficiency in the functioning of these various boards or reduced expense in their operation would be accomplished by consolidating all of them in a single department.

2. The group having to do with the regulation of financial institutions:
   The Banking Department
   Bureau of Building and Loan Supervision
   State Insurance Department.

The Committee came to the conclusion that the consolidation of any one of these three with either of the others, or the inclusion of one or all in any other departmental group was impracticable.

3. The agencies which, while vested with power by the state legislature, have to do primarily and almost solely with problems of a local nature practically independent of the state government proper. In addition to the Reclamation Board, the Irrigation Board, and the California Redwood Park Commission, the Committee placed in this class practically the same agencies grouped in the present survey under the designation of regional administration.

4. The Board of Prison Directors, because it is a constitutional body and hence beyond the reach of legislative enactment.

5. The Civil Service Commission, which in the opinion of the Committee should be wholly independent of any other state agency or department.

6. The Legislative Counsel Bureau, which the Committee properly recognized as a legislative and not an administrative agency.

7. The State Library.

8. The Advisory Pardon Board, which, from the nature of its work, it was felt should not be grouped with any other agency.

9. The Adjutant General, whose duties as military aide of the Governor were not considered to be co-ordinate with those of any other state department, board, or commission.

10. The following agencies:
    Industrial Accident Board
    Industrial Welfare Commission
    The Commission of Immigration and Housing.

The Committee determined that, on account of the quasi-judicial functions and the special field of activity coming within the jurisdicton of these bodies, they could function best independently of one another or of any other state agency. Provision was made, however, for their close co-operation through an Advisory Council of Labor which is referred to below.

11. The California Historical Survey Commission.

After these various exceptions had been made, amounting to the exclusion of more than thirty agencies from the operation of the Committee's recommendations as to consolidation, seventy remained to be dealt with in this way. The plan consisted in the creation of ten superior administrative units, in charge either of single directors or of boards consisting of a varying number of members. These ten departments were to be as follows:

1. Department of Finance
2. Department of Trade and Corporations
3. Department of Works
4. Department of Agriculture
5. Department of Natural Resources
6. Department of Labor
7. Department of Education
8. Department of Public Health
9. Department of Institutions
10. Department of Social Service.

Two officers of the Department of Finance and the directors or chairmen of the other nine departments were recommended to constitute the Governor's cabinet of eleven members as follows:

1. Director of Receipts and Supplies
2. Director of Accounts and Expenditures
3. Director of Trade and Corporations
4. Director of Public Works
5. Director of Agriculture
6. Director of Natural Resources
7. Director of Labor
8. Director of Institutions
9. Chairman of the Board of Education
10. Chairman of the Board of Health
11. Chairman of the Board of Social Service.

The process of consolidation from which the above organization would result will perhaps be made clear by the following summary of the organization and powers of the new departments.

Department of Finance.—The Committee's recommendations could not touch the organization of functions of the constitutional offices dealing at present with financial matters, i. e., the Controller, Treasurer, Board of Equalization, and Secretary of State.

The most significant changes in the statutory agencies were involved in a redistribution of the functions of the Board of Control. The three important functions of that body as at present constituted are: 1. the control of departmental expenditures by (a) a budget system, and (b) a pre-audit system which provides close scrutiny of all state expenditures before they are incurred as well as a careful audit of claims growing out of the authorized expenditures; 2. the installation of uniform systems of accounts for and the periodic audit of all agencies; 3. the investment of state funds, making appropriations (with the Controller) from the emergency fund, counting the money in the treasury, and establishing the financial policies of the state.

The Committee proposed that the important pre-audit system of the Board of Control, which it found is now becoming unwieldy because of the rapid growth of the state, be placed with the respective chief executives in the departmental group.

They assigned to the Department of Finance, the functions of the State Purchasing Department, Motor Vehicle Department, State Printing Office, and Corporation License Tax Exemption Board. The functions of these, together with the remaining activities of the Board of Control, were to be distributed among the following branches of the new department:

1. Director of Accounts and Expenditures, and 2. Director of Receipts and Supplies (the allocation of the duties to be made by the Board of Finance): To prescribe uniform systems of accounting and reporting for all offices, departments, and institutions; to pre-audit expenditures of agencies not included in the cabinet group; to audit, periodically, accounts of all officials, departments, and institutions; to supervise organization and investigate efficiency of administration of state business and functions; to prepare and publish statistical data pertaining to the operation of the state government; to supervise state purchasing and approve all contracts; to supervise the acquisition and disposition of all state property and equipment and require periodic inventories and reports; to operate the State Printing Office; to supervise motor vehicle taxes; to administer the Orphan Aid Act.

3. Board of Finance (the Director of Accounts and Expenditures, the director of Receipts and Supplies, and the State Controller, the chairman to be designated by the Governor): To prepare the state budget; to invest state funds; to make appropriations from the emergency fund; to count the money in the treasury; to hear corporation license tax appeals; to sit as Corporation License Tax Exemption Board; to recommend legislation where necessary to effect modernization of state business methods.

The Director of Accounts and Expenditures and the Director of Receipts and Supplies were to be appointed by and hold office at the pleasure of the Governor and both were to be members of the Governor's cabinet.

Department of Trade and Corporations.—This department was to embrace the functions now exercised by the following agencies:

Railroad Commission
Corporation Department
Market Director
Department of Weights and Measures.

It was recommended that the President of the Railroad Commission be the director of the department, with power to appoint the chiefs of such divisions as he might create to administer the functions not coming within the jurisdiction of the Railroad Commission.

Department of Public Works.—This department was to embrace the functions now assigned to the following agencies:

Department of Engineering
Highway Commission
Capital Planning Commission
Water Commission
Carey Act Commission
Superintendent of Capitol Building and Grounds
The trustees, etc., of various memorial properties
Capitol Commission.

It was recommended that there be created a Director of Public Works, to be appointed by and hold office at the pleasure of the Governor; that the work be divided into the following divisions; and that each division be placed under the direction of a chief of division to be appointed by and hold office at the pleasure of the director:

1. Division of Highways
2. Division of State Buildings
3. Division of Irrigation and Water Rights
4. Division of River Improvement
5. Division of Public Buildings and Grounds.

It was recommended that the Director also serve as chief of one of the divisions. It was further recommended that there be created a special Highway Commission of three members whose sole function should be the selection of highway routes throughout the state. This commission was to be appointed by the Governor and receive a per diem compensation and necessary traveling expenses.

It was recommended that the present practice of having the chief engineer of the Board of State Harbor Commissioners of San Francisco appointed by the Engineering Department, or in this instance, the Director of Public Works, should be continued.

It was recommended that the Chief of the Division of Irrigation and Water Rights should have authority to pass upon applications for the appropriation of water, and that his decisions should be subject to review by a Board of Appeal, composed of the Director of Public Works and the chiefs of two other divisions, of his selection.

It was recommended that the functions of Port Warden for the Port of San Francisco be administered by the Board of Harbor Commissioners of that port.

It was recommended that the Governor be empowered to appoint a local unpaid trustee for each of the memorial and historical properties placed under this department.

Department of Agriculture.—This department was to embrace the functions then exercised by the following agencies:

State Board of Agriculture
Horticultural Commission
State Dairy Bureau
State Veterinarian
Stallion Registration Board
Cattle Protection Board
Board of Viticultural Commissioners
Land Settlement Board
Board of Citrus Fruit Shipments.

It was recommended that there be created the office of Director of Agriculture, to be appointed by and hold office at the pleasure of the Governor; and that a chief, responsible to and appointed by the Director, be placed at the head of each of the following divisions (except that the Director should serve as chief of one of the divisions, and that the Division of State Fairs should be administered by a Board of State Fair Managers, to be appointed by the Governor, with the Director of the Department of Agriculture as ex officio member thereof, the chairman of the Board of Managers to serve as ex officio Regent of the University of California):

1. Division of Plant Industry
2. Division of Animal Industry
3. Division of Land Settlement
4. Division of State Fairs.

Department of Natural Resources.—This department was to embrace the functions now exercised by the following agencies:

State Mining Bureau
Trustees of State Mineral Cabinet
State Board of Forestry
Fish and Game Commission
Surveyor General.

It was recommended that there be a director appointed by and holding office at the pleasure of the Governor, and that a chief, responsible to and appointed by the Director be placed at the head of each of the following divisions (except that the Director should serve as chief of the Division of Mines and Minerals):

1. Division of Fish and Game
2. Division of Land
3. Division of Mines and Minerals
4. Division of Forestry.

Department of Labor.—The functions of this department under the control of a Director of Labor to be appointed by and to hold office at the pleasure of the Governor, were to embrace all the present functions of the Bureau of Labor Statistics, including the operation of the state employment bureaus.

The Committee also recommended that there be created an Advisory Council of Labor to consist of the Director of Labor as chairman and one representative from each of the following named agencies:

Industrial Accident Board
Commission of Immigration and Housing
Industrial Welfare Commission
Department of Education
Department of Health.

It was to be the duty of this Council to prevent overlapping and duplication of the social and industrial welfare agencies which it represented.

Department of Education.—This department was to embrace the functions now performed by the following agencies:

State Board of Education
Superintendent of Public Instruction (and assistant superintendents)
State Normal Schools
California Polytechnic School
California School for Deaf and Blind.

The Committee recommended that there be a Board of Education to administer this department, consisting of five lay members, and that the Superintendent of Public Instruction be its chief executive officer.

It also recommended that the functions now exercised by the local boards of trustees of the normal schools and the two other state schools be performed under the supervision of the State Board of Education, which should appoint the president of each of the normal schools and the principals of each of the special schools. There should be also, it was the opinion of the Committee, a local board of trustees for each of these schools to serve as an advisory and visiting committee without compensation. The principal function of these boards should be to form a connecting link between the state government and the communities in which they are located.

Department of Health.—The State Board of Health was to continue practically as at present constituted and empowered, except that it should consist of five instead of seven members, the chairman to be a member of the cabinet.

Department of Institutions.—The department was to embrace the functions now exercised by the following agencies:

Veterans' Home
Women's Relief Corps Home

Industrial Home for Adult Blind
Pacific Colony
State Hospitals
Commission in Lunacy
Preston School of Industry
Whittier State School
California School for Girls
Bureau of Criminal Identification and Investigation.

It was recommended that the functions of this department should be under the control of a Director appointed by and holding office at the pleasure of the Governor; that the Director should appoint the superintendents of the various institutions, by and with the consent of the cabinet; and that provision should be made for the retention of local unpaid boards of managers for these institutions, to serve as advisory and visiting boards and to form connecting links between the state government and the communities in which they are located.

Department of Social Service.—The State Board of Charities and Corrections was to be constituted and empowered, practically as it is at present except that it should consist of seven instead of six members and that it should be appointed by the Governor without the requirement of advice and consent of the Senate.

Three other sets of recommendations of the Committee should be noted.

It advised that the Civil Service Commission, consisting of three members serving overlapping terms of four years with compensation of $3,000 a year each, should be reorganized so as to consist of one member at a salary of $5,000 a year, and two members on a per diem basis of $10 a day, not to exceed $300 a year each and necessary traveling expenses, and that the same provisions as to tenure, appointment, and removal should be continued.

The Committee advised a reorganization and centralization of the legal service of the state. At present a large number of state agencies are served by separate legal advisers, although the Constitution constitutes the Attorney General the general legal adviser of the state government. The Committee recommended that the position of special attorney for each of the following seven departments be abolished, and that the legal service of the departments be performed in the Attorney General's office, with the addition of two deputies to his present force:

State Board of Health
State Commission in Lunacy
Cattle Protection Board
State Board of Harbor Commissioners
State Market Commission

State Mining Bureau
State Water Commission.

It believed that in the other departments efficiency would be impaired and expense increased if present arrangements were disturbed.

Finally, the Committee propounded certain general recommendations dealing for the most part with the financial procedure of the state. Included in these recommendations were the following, relating more specifically to organization: that the present practice of setting salaries by statute, so far as it referred to employees and officers other than heads of departments and chief deputies, be discontinued; that those sections of the law which now provide for such salaries be repealed and provision be made for the payment of salaries out of the support funds of the various departments; that the statutory provision for the State Commission on Voting and Balloting Machines be repealed; and that the administrative offices of the state should be centralized at Sacramento, the seat of the state government, so far as the efficient performance of the public business should permit.

It would be easy to find objects of criticism in the recommendations of the Committee on Efficiency and Economy: The exemption of so many agencies from the scope of the plan proposed; the failure to advise the abolition of a number of agencies whose services could probably without impairment of efficiency be dispensed with; the continuance of others as separate entities simply grouped for convenience under a common head; the proposed allocation of existing agencies among the newly created departments—such matters might be pointed to as errors of judgment. But these are matters upon which there could be differences of opinion and on which there are differences of opinion among experts. The Committee was forced to decide, too, between devising a plan which was in all respects perfect from the scientific point of view and one which would at the moment be possible of realization and likely to survive the reactions of the less progressively constituted political mind. But the report presented the fundamentals of a proper system of administrative organization—clearly defined channels of authority and responsibility, co-operation or co-ordination of allied functions, and centralization of control in the chief executive power with provision for correlation, counsel, and advice. It contained the elements of a feasible plan upon which future changes could be builded, as the public became more enlightened as to its advantages. In the careful judgment of its proponents it would effect an actual saving of over one-half million dollars each biennum, not counting the probable benefits in money and service which would result from increased efficiency. The proposed plan of reorganization was to be criticised on the score that it did not go far enough. It was too conservative rather than sufficiently radical.

In view of this estimate of the plan, which is concurred in by experts in the field of public administration, and also in view of his own instructions to the Committee and explanations to the Legislature, the Governor's evaluation of the scheme and its effect upon the movement for reorganization is important. In a special message to the Legislature of March 20, 1919, in which he transmitted the report of his Committee, Governor Stephens, after praising the labor generously expended on the report and remarking on its value as a public document, said:

> The committee has apparently felt constrained to propose a new plan, which is a substantial departure from those methods and agencies now existing. A somewhat radical change is proposed in our methods of administration when it is proposed to substitute, in place of most of the existing commissions, a system of departments and bureaus, with directors, chiefs of divisions, and minor heads, all holding office directly or indirectly at the pleasure of the Governor.
>
> To change the laws of California to provide for a complete reorganization of the structure of the state's government is a task so huge that there is little hope that it can be accomplished in the remaining days of this session of the Legislature. Indeed, the work is so important and the results which may follow such changes so vast that the members of the Legislature and the people of the state should have ample time for careful consideration and study. I am convinced that they are not interested so much in the structure of government as they are in an immediate reduction of the cost in the maintaining of the high standard of efficiency. The plan of government is important mainly as it reflects itself in economy and in efficiency.
>
> . . . I am firmly of the opinion that the Legislature at this session should go as far as possible in the enactment of measures tending towards consolidation of certain commissions, where it is certain that such consolidation will not result in lessened efficiency and will with equal certainty result in the lessening of cost. . . .
>
> . . . One of the criticisms directed against the suggested reorganization of the administrative structure of government into a number of departments, all under the control of appointees to hold office at the pleasure of the Governor, is that such arrangement would place tremendous power in the hands of the Chief Executive. While it may be wise to centralize power if at the same time responsibility is also centralized, yet the question is of such serious concern that it seems ill-advised to act precipitately. . . .
>
> . . . There is an element in our body politic that persistently aims at a retrenchment calculated to impair and destroy agencies of government that protect the people from the forces of special privilege. Allow me to repeat what I have frequently publicly declared, that I will not approve and will resolutely oppose any backward step in the government of our state. . . .

In spite of the fact that the legislative session was drawing to a close and that the reorganization plan must proceed without vigorous executive support, separate bills embodying some of the recommendations of the Committee were introduced, but only one of these, that creating the Department of Agriculture, in slightly different form from that recommended by the Committee, became a law.

4. REPORT OF THE TAX PAYERS' ASSOCIATION OF CALIFORNIA

While the Committee of Efficiency and Economy was at work, the Tax Payers' Association of California prepared a report on the subject of reorganization which was published in January, 1919, in time for the beginning of the legislative session. While this plan was presented to the Legislature, no progress was made, and the Legislature finally adjourned without taking any action on the bill. The Tax Payers' Association plan was based upon a transfer of functions without elimination of any function now performed by the state government. It contemplated the assembling of existing state agencies into twelve departments, in each of which, where there were subdivisions or organizations, the departmental organization was to be a "board" composed of the chiefs of those divisions. These departments were to be the following:

Department of Finance.—Five members (Board) consisting of Chairman of Board of Equalization, Controller, Treasurer, Chief of Division of Control, and Chief of Division of Purchasing and Printing.

Department of Law.—Single head—Attorney General.

Department of Sanitation and Hygiene.—Three members (Board) consisting of Chief of Division of Health, Chief of Division of Foods and Drugs, and Chief of Division of Housing.

Department of Commerce and Labor.—Five members (Board) consisting of Chief of Division of Corporations, Chief of Division of Markets, Chief of Division of Harbors, Chairman of Raiload Commission, and Chairman of Industrial Accident Commission.

Department of Charities and Welfare.—Single head.

Department of Corrections.—Three members (Board) consisting of Chief of Division of Administration, Chief of Division of Pardons and Parole, and Chief of Division of Criminal Identification. Prison Directors in charge of prisons.

Department for Care of Defectives.—Single head.

Department of Conservation.—Three members (Board) consisting of Chief of Division of Forestry, Chief of Division of Fish and Game, and Chief of Division of Custody.

Department of Defense.—Single head—Adjutant General.

Department of Public Works.—Single head—State Engineer.

Department of Natural Resources.—Five members (Board) consisting of Surveyor General (Chief of Land Division), Chief of Water Division, Chief of Division of Agriculture, Chief of Division of Mining, and Chief of Division of Animal Industries.

Department of Education.—Five members (Board) consisting of Superintendent of Public Instruction, Chief of Division of Instruction, Chief of Division of Administration, Chief of Division of Library, and Chief of Division of Historical Research. University of California to be conducted by a Board of Regents as at present.

5. REORGANIZATION MEASURES BEFORE 1921 LEGISLATURE

The subject of reorganization early became a matter of discussion in the forty-fourth session of the Legislature which convened January 3, 1921, due to the urgent need for increased revenue and the attention which was thus naturally directed to the possibilities of economy in administration.

The state budget for the ensuing biennium prepared by the Administration called upon the Legislature for total appropriations of approximately $81,388,000 as against $52,786,000 for the previous biennium. Part of the increased demand of nearly twenty-nine millions additional revenue was to be accounted for by measures approved by the people at the general election of November 2, 1920, for additional state aid to education and charitable institutions and assumption by the state of all interest payments on highway bonds, part of which interest had previously been apportioned among the counties. But after these further burdens upon the state treasury had been accounted for there remained approximately fourteen millions which must be charged to increased cost of government. The Administration proposed to meet the increased requisition for revenue by a revision upwards of the rates of taxation on the income of public utility corporations, banks, and insurance companies from which, under the existing system of taxation, the state derives its principal revenue. This fiscal proposal was introduced in the form of the so called "King bill."

The provisions of the King bill and the opposition which developed to it naturally led to discussions of economy and efficiency. These discussions precipitated certain suggestions for reorganization made by the Governor in a special message of January 18, 1921, and were given concrete form in bills introduced on the same day. Shortly thereafter the Taxpayers' Association of California secured the introduction of proposals embodying a plan which had been prepared by it and which differed from the plan presented by it in 1919.

The bills which dealt with governmental reorganization before the Legislature may therefore be divided into two classes. The first class included a group of eight bills which represented the limit and extent to which the present Administration favored a consolidation and coordination of the numerous state boards and commissions and the consequent reduction of expenditures. The other class consisted of the measures sponsored by the Taxpayers' Association, representing the views and aims of that organization as to the extent to which California might go in the direction of reorganization and the reduction of governmental costs.

In recommending his reorganization measures to the favorable consideration of the Legislature, Governor Stephens stated their object to be "the abolition of many boards and commissions; the elimination of duplication and overlapping, and the consolidation, so far as our constitution, laws, and the public good permit, of such governmental agencies and activities as efficiently and economically grouped themselves together."

He stated further that—

> The bills respond to a prevailing present-day judgment in favor of centralization of power and consequent fixing of certain responsibilities. . . . The movement is toward centralization, the elimination of separated boards and offices with duplicated functions, and the substitution therefor of single departmental heads. . . .
>
> The clearly declared policy is to vest in the Governor the civil administration of the laws, and to divide the general subject of executive and administrative work into departments with heads appointed by the Governor, responsible to the Governor and holding office at his pleasure. . . .
>
> The power is expressly given to the head of each department, subject to the approval of the Governor, to arrange and classify the work, to adopt necessary rules and regulations and to assign to the employees thereof such labors as may be conducive to the utmost efficiency. . . .
>
> While a substantial financial saving will be accomplished by the adoption of these reorganization laws, in my judgment a greater money saving as well as increased efficiency will be attained by this grant of power to the department heads to assign all the employees of the department, and . . . with the approval of the Governor to create additional divisions as the needs of the department may require. . . .
>
> No single function or duty of the state is by any of these measures curtailed or discontinued. On the contrary the fusion or merger of activities will give us the much desired economy, and, at the same time, a greater efficiency and a more beneficial functioning than we have attained in the past. . . .
>
> I am firmly convinced that the reorganization of our government along the lines indicated will be a marked step forward. Indeed, I am hopeful that the result of the present changes may be a complete justification for a more comprehensive reorganization of our state activities.

The first bill of the Administration group formally transferred the powers of the present boards and commissions to the new departments created by the seven other bills.

The second bill created a Department of Finance, into which it proposed to consolidate the functions of 30 existing boards and commissions. The work of the Department of Finance was divided into seven divisions, as follows:

Institutions
Budget and Accounts
Purchases and Custody
Printing
Motor Vehicles
Capitol Building and Grounds
Libraries and History.

It was provided that the department should be administered by a governing body consisting of the chiefs of the divisions of institutions, budgets and accounts, and purchases and custody, who also ex officio were to constitute the State Board of Control and the Corporation License Tax Exemption Board.

The third bill added to the present Department of Agriculture the powers and duties of the Superintendent of Weights and Measures, Board of Forestry, Fish and Game Commission, Market Director, and Market Commission.

The fourth bill provided for a Department of Education into which was merged the powers formerly exercised by the State Board of Education and numerous institutional boards, including the boards of trustees of the several state normal schools. It provided that the department should be under the control of an executive officer to be known as the Director of Education and constituted the State Superintendent of Public Instruction ex officio Director of Education. The bill required that the work of the department should be divided into at least two divisions to be known as:

Division of Textbook, Certification, and Trust Funds, to be in charge of the State Board of Education which was continued in force with all its existing powers and functions;
Division of Normal and Special Schools.

A Department of Public Works was created by the fifth bill. The work of this department was divided into:

Division of Engineering
Division of Irrigation
Division of Highways
Division of Lands.

This organization was to result from the consolidation of offices of State Engineer and Engineering Department, Land Settlement Board, Water Commission, Highway Commission and Highway Engineer, and Carey Act Commission. The general purpose of this bill was to centralize in one department all of the construction work performed by the state. The department was to be conducted under the control of an executive officer to be known as the Director of Public Works and State Engineer. In conjunction with this officer there was to function a Board of Public Works to consist of the Governor, the Director of Public Works and State Engineer, the chief of the Division of Irrigation, and three appointive members to be appointed by the governor. The duties of the board were to be to consider and advise upon matters of department policies and plans of development.

The sixth bill created a Department of Labor with a Director of Labor at its head. The bill abolished the present Bureau of Labor Statistics and its Commissioner, the Industrial Welfare Commission, and the Commission of Immigration and Housing and consolidated their functions in the new Department of Labor. The department was to be divided into at least two divisions:

Division of Employment and Statistics, of which the Director of Labor was to be chief
Division of Industrial Relations.

The Department of Professional Standards, created by the seventh bill, merged the duties heretofore exercised by numerous state boards, abolishing the following: accountancy, architecture, dental examiners, embalmers, library examiners, medical examiners, optometry, pharmacy, and veterinary medicine. The administration of the department was to be entrusted to a Director of Professional Standards.

The last change, embodied in the eighth bill, was one affecting the Civil Service Commission. It substituted in lieu of the present commission of three members each of whom were to receive a salary of $3,000, a board consisting of three members, one of whom was to be the executive member, with a salary of $5,000, and the other two of whom were to be associate members with a per diem allowance not to exceed $300 per year. It will be noticed that this proposal accorded with the recommendation of the Committee on Efficiency and Economy of 1919.

The second reorganization project, consisting of the changes being fostered by the Taxpayers' Association, called for a more complete readjustment of administrative machinery and was to abolish all but five of the present statutory agencies, retaining these and, by necessity, those agencies created by constitutional provision.

The program called for the creation of thirteen departments in the executive branch of the state government, with a salaried director as the chief executive officer of each, and was to transfer to such departments all of the functions, powers, and duties of the numerous agencies abolished. The contingency of conflicting authorities and the overlapping and duplication of functions between the various departments was provided against by the extension of ample power to the Governor to adjust any such questions. The proposed departments were to be the following:

Department of Finance
Department of Harbors
Department of State
Department of Correction
Department of Corporations
Department of Natural Resources
Department of Education
Department of Labor
Department of Health

Department of Welfare
Department of Institutions
Department of Public Works
Department of Agriculture.

The State Board of Health was not included in the plan for reorganization as given in these bills for the reason that this Board rests upon a constitutional provision and therefore its status is not subject to reorganization legislation.

Due to the time given to the discussion of taxation and other matters, it was for a long time doubtful that any action would be taken on the reorganization measures before the Legislature. This doubt was made more positive by the fact that the final passage of the King bill had the effect of insuring more than enough revenue to operate the state government as at present constituted and of relieving the Administration of the necessity of vigorous prosecution of its reorganization proposals which were closely bound up with the revenue bill, and by the fact that it was quite certain that the Administration was definitely opposed to the Taxpayers' Association plan. It was certain that the Administration easily had control of the majority in both houses of the Legislature and was therefore in a position to control the situation.

However, in the closing hours of the session, with little or no debate, the eight Administration bills were permitted to pass. The only opposition which developed related to the inclusion of the Board of Forestry and the Fish and Game Commission in the new Department of Agriculture and the changing of the status of institutional agencies from directory to purely advisory boards. Only one of these objections survived as an amendment passed to the third bill, excluding the Fish and Game Commission from the Department of Agriculture.

It may be said that the plan, which goes into effect on July 29, 1921, effects only a slight improvement by reason of its grouping together of certain related agencies. Practically no reduction in the agencies of central government is made. It is doubtful if any great economy in expenditure will result. It is regarded as unfortunate by many that the Administration did not revert to the recommendations of the Efficiency and Economy Committee and put into effect the plan proposed by that body. It is hoped, however, that the first step in the right direction has been taken and that this Administration or its successor will be prevailed upon to go further on the road to effective reorganization.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. PLACE OF SCIENTIFIC RESEARCH IN STATE GOVERNMENT

Upon the data which has been presented in this report, the following conclusions are made and recommendations offered upon the place which scientific research should have in state administration.

1. The administrative agencies of the state engage to a limited extent only in the work of scientific research. They are primarily concerned with the administration of previously ascertained standards, having either not the time or the facilities or the inclination to submit their processes to the test of systematic reinvestigation. It was stated by an official of the Department of Agriculture, one of the very few agencies in which research proper is carried on, that its work was "ninety to ninety-five per cent administration; five to ten per cent research."

2. The scientific work conducted by the departments, limited as it is, is of a nature peculiar to the department concerned in each case, and is so closely allied with particular administrative problems that it must be carried on in close connection with those problems and under the jurisdiction of the agency in which the solution of the problem is being sought. This would seem to preclude the possibility, in any reorganization of state administration, of setting up a great department of research which would be the central laboratory for the working out of all problems of a scientific nature which might arise in the administration of state government, and which would represent the state as a whole in any conference of state and national agencies which may result from the study of the situation now being made throughout the country.

The only state official who considered favorably the idea of such a department of research was, rather curiously, the chief of the Children's Department of the State Board of Control. "I now have in my files," she said, "a great mass of data which I should analyze in order to proceed intelligently with my administrative work, and yet the administrative work of my office is so large I have no time for the study which should come first. I should welcome the existence of a state research department to which I could submit my data for the necessary study and report."

The almost universal feeling is expressed, however, in the statement of another intelligent and sincere official that "administration and research do not mix." In other words, it is felt that organization of the state departments on a basis of administrative functions would conflict with a department of research based upon a separate object of organization. The department of research would be placed, almost inevitably, upon the same plane as the administrative departments and would be subjected to all the conflicting interests which exist among them including, it must be remembered, the political.

3. There is a large number of activities in the state administration of California concerned with the field of human relations. These depend to some extent at the present time, and would rely to a greater extent after research has been accorded fuller recognition, upon scientific investigation for their proper functioning. In fact, there are two main groups of agencies involved in the field of science: one, the group dealing, for the most part, with the natural resources of the state, involving the physical sciences; the other, and numerically larger group, dealing with the well-being of the people, involving the social sciences. There is serious question whether these two groups would have enough in common to make it possible to tie them together in any form of organized relationship. The closest bond is that of medical science, which is the common aid of nearly all of the social agencies. It is socialized medicine, however.

4. It is true that great reliance is placed by nearly all of the state agencies upon the institutions of higher learning in the state, especially the University of California. The apparent aversion to a central research department does not extend to the state university—that is, from the point of view of its being a great recruiting center from which may be called, as occasions arise, experts to come to the agencies to solve their scientific problems. When the Board of Fish and Game Commissioners desires a study to be made of the game birds of California, it calls upon the University of California to lend it an economic ornithologist; when the Board of Charities and Corrections or the Commission in Lunacy desires the solution of a proper dietary for the inmates of state institutions, based upon their needs and habits, it calls upon the University of California to designate the professor of nutrition for the task.

But while there is no hesitancy about calling for the university expert to come to the departments and work under their jurisdiction, there is considerable disinclination to transferring their research work bodily to the university because of a fear of lack of understanding on the part of the academician of the practical administrative features involved. Research must be made to serve administration; it must not become research for research's sake. To insure this, it must be under the direct control of the particular administrative department concerned in each case. This attitude of the state official is probably accountable for the recent removal of the Division of Chemistry of the Department of Agriculture from Berkeley to Sacramento and for the recent agitation for the similar removal of the Hygienic Laboratory of the Board of Health from the University to the Capital.

5. The large degree to which organization for scientific research will depend upon the reorganization of state administration has already been

made evident. It has been pointed out that the best thought of political science requires that authority and responsibility must be combined in administration; that departments must be functionalized, that is, that there must be a grouping of related activities into single sections, divisions, and departments according to the functions performed; that in charge of each such units of administration there must in most cases be a single executive with complete authority over it and full responsibility to the next highest executive, the increasing degree of authority and responsibility culminating in the supreme executive or governor, whose power is made complete by virtue of his control of the tenure of all subordinates; and that the process of consolidation must be carried far enough so that for consultative, advisory, and co-ordinative purposes, the heads of the primary departments of administration may constitute a small compact group or cabinet.

When the state administration has been reorganized according to these principles, the problem of effecting co-ordination for the conscious recognition and encouragement of scientific research will not be difficult to solve. Within each main department the work will be so ordered and arranged that the research function will find its proper place, and the department will be of sufficient size to support adequately a properly appointed research laboratory. Moreover, concerning the state administration as a whole, it can be said that while the process of consolidation demands the placing of executive power in a few hands, it does not preclude, but on the contrary makes more easy, the introduction of the advisory function. The purpose of reducing the state administration to a small number of primary departments is to make possible the creation of a body for giving advice to the chief executive and providing consultation and co-operation among its members. No sound principle is violated if for certain other purposes the heads of departments or some of them constitute councils of various sorts for special consultation, or if additional members be introduced upon such councils for the purpose of giving representation to lay or expert interests in an advisory capacity. It will be recalled that such a council for the representation of the labor interests of the government was included in the recently proposed plan of reorganization in California.

2. ORGANIZATION OF A STATE SCIENTIFIC COUNCIL

Granted the creation of a departmentalized state administration, the ideal plan for the organization of scientific research within the state government in the light of the above conclusion would seem to be the creation of a *Scientific Council* or *Council on Scientific Research* which should be composed first, of the heads of those departments in which functions of a scientific nature are or might be carried on; second, representatives of the great academic institutions and of the various scientific societies within the state; third, representatives of the great industrial enterprises within the state which would expect to benefit from the scientific conduct of the state departments and which in turn could aid such work by their intelligent support. While the Council should necessarily require the service of an expert bureau for the administration of its functions it should not constitute a central research laboratory but should rely upon the separate research divisions of the various departments for the actual solution of scientific problems.

The advantage of such a form of organization would be that while it would imply a conscious recognition of the field of science, it would not in any way produce a rigidity of system and formality of procedure. Leaving freedom of action to departments to work out their own problems, it would definitely co-ordinate the efforts of all in a single direction. The Council would serve as a great clearing house between departments, between the state and councils in other states, and between the state and the nation. It would pool facilities and avoid duplication. It would place the research equipment of the whole country at the disposal of a single state department. Its mere existence would be an earnest of the vital importance of the scientific method in the whole field of human relations.

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A GENERAL SURVEY OF THE PRESENT STATUS OF THE ATOMIC STRUCTURE PROBLEM

Report of the Committee on Atomic Structure of the National Research Council[*]

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[*] This committee of the Division of Physical Sciences of the National Research Council consists of the following members: F. A. Saunders, Chairman, P. W. Bridgman, Irving Langmuir, G. N. Lewis, R. A. Millikan, Leigh Page, D. L. Webster. The late Professor H. A. Bumstead was chairman of the committee as originally constituted and much of the work preliminary to the preparation of the report was done under his leadership.

PART I

THE PRESENT CONCEPTION OF ATOMIC STUCTURE

BY DAVID L. WEBSTER

PROBLEMS AND METHODS

A hundred years ago, when Dalton first used the idea of atoms, there was no question of atomic structure. The very name "atom" meant "indivisible," and an atom was supposed to be the last stage in the division of matter. At that time there was no way of knowing how small an atom was. Since then, it has been found to be about ten thousand times as small as the smallest particle whose structure we can see at all, even with a microscope. Nevertheless it appears that the atom has a structure, and not only that, but that along with the problem of atomic structure we now have the problem of atomic dynamics as well.

These problems date, practically, from the discovery of the electron. Maxwell,[1] in 1869, had explained the dispersion of light in a prism by the forced vibrations of minute electrified particles in the material of the prism. And in 1897, Sir J. J. Thomson[2] proved that cathode rays were indeed just such electrified particles as Maxwell had spoken of, and that they were smaller and lighter than any atoms. Then it appeared, from the study of cathode rays, that these minute particles were all exactly alike, no matter what sort of material they were extracted from, and that the mass of each one of them was only about one two thousandth part of that of a hydrogen atom. So they were given a new name, "corpuscles," or "electrons," and they were assumed to be the most important units of which all atoms are built up,—not the only units, however. For the electrons are always charged negatively, and an atom is often as a whole electrostatically neutral, or even positive. So there must be positive electricity in it also. But the only positively charged particles that have ever been isolated, as electrons have, are positively charged ions, and they may be identified by their much greater masses as practically whole atoms. So the electrons, or negative corpuscles, being so light and mobile, are more in evidence in most phenomena than the positive electricity. Thus the first problem of atomic structure is how many of these electrons there are in any atom, and the next is what sort of positions they occupy.

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[1] J. C. Maxwell, *Math. Tripos Exam.*, 1869.

[2] J. J. Thomson, *Phil. Mag.*, **44**, 293, 1897.

On the number of electrons, we have, fortunately, some reliable information in the fact predicted by Thomson, that the scattering of X-rays is done primarily by individual electrons, without cooperation. Thus the number of electrons per atom may be counted by measuring the scattering power per atom. This has been done by Barkla,[1] who found that, for light elements at least, *the number of electrons is probably equal to the ordinal number of the element in Mendeleyeff's table*, thus: Hydrogen has 1, helium 2, lithium 3, carbon 6, fluorine 9, neon 10, sodium 11, chlorine 17, argon 18, potassium 19, etc. This important discovery is confirmed by all subsequent work, especially by Moseley's[2] discovery of the great importance of this "atomic number" as the determining factor in X-ray spectra. With this point established we can attack the next important problem, that of the positions of the electrons.

Since we must get our information indirectly, by inference from observed phenomena, the question arises, what phenomena are the most reliable guides in this matter? All the phenomena we can observe depend on the structure of the atoms concerned in them, and because the electrons are light and mobile, the presumption is that any phenomenon we choose is likely to be due to them. Practically, however, most of our evidence to date has been derived from two classes of data, those of chemical statics, and those of spectroscopy. The theory finally accepted must of course fit both these classes of data and many others, but strange to say, the results obtained from these two classes to date have been very discordant. Thus the first problem is to consider the reliability of these classes of evidence, not as to details of the final model, but for a mere rough outline of the structure. For this purpose data of the chemical type have several distinct advantages:

First, the chemical data relate to phenomena involving a few electrons at a time and give some evidence on all of them, while the spectroscopic data deal primarily with only one electron at a time, but always involve essential and complex corrections due to all the rest. This makes the chemical data give a more satisfactory picture of the relations between electrons.

Second, the chemical data are much more numerous than the spectroscopic, and the chemical properties of the elements differ in quality as well as quantity, and so their significance is much more readily grasped by our minds, although they may actually be no more important in the final analysis; thus the chemical data are to the atom what a photograph is to a man, while the spectroscopic data are its Bertillon measurements; neither class alone gives a complete identification, but the photograph conveys an impression of his appearance more readily than the measurements.

[1] C. G. Barkla, *Phil. Mag.*, **21**, 648, 1911.

[2] H. J. G. Moseley, *Phil. Mag.*, **27**, 703, 1914.

Third, and perhaps most important, is the fact that the data of chemical statics give evidence on the *structure* of the atom, with very little reference to its *dynamics* except in a statical or quasi-statical aspect, while the spectroscopic data deal with electrons engaged in motions of a type that do not occur in the quiescent atom, and thus they are impossible to interpret without a knowledge of atomic dynamics as well as structure.

On the other hand, while we form an idea of a man better from his photograph than from his Bertillon measurements, the latter are more reliable as a means of sure identification, although even they are not perfectly reliable; and also the very fact that chemical statics gives evidence only on the structure of the atom and on atomic statics makes it necessary to look to the data of spectroscopy, chemical dynamics, etc., for our knowledge of atomic dynamics.

THE POSITION OF THE ELECTRONS

In the evidence from chemical statics, we have not only the well-known tetrahedral form of the carbon atom, but a great mass of evidence in Mendeleyeff's table and in the recent discoveries of Laue, the Braggs, and others on the structures of crystals. All this evidence points to a type of structure described first by G. N. Lewis,[1] and developed further by Langmuir,[2] and it strongly suggests a system of atomic statics much like one developed by Parson.[3] The following account of this theory is a mere sketch, intended to show its general character and its relation to other theories, and for details the reader is referred to the papers on this subject by Lewis, Langmuir and Parson.

According to this theory, the atom has the positive electricity concentrated in a very small massive "nucleus," for reasons to be discussed below, and the electrons are distributed around it. Each electron is assumed to occupy a certain "cell," and may be at rest within that cell, so far as the evidence of chemical statics will tell us. Whether they are at rest or not is a matter of atomic dynamics. The spatial arrangement of these cells, and the forces acting between electrons in different cells, must be such as are suggested by the chemical evidence.

In this evidence, one of the most important points is the tendency of such elements as the alkali and alkaline earth metals to form positive ions, and of the halogens and a few others to form negative ions. This fact may be combined with the fact that each element has as many electrons as its ordinal number in the periodic table, and from these facts we see that any of these ions, positive or negative, has exactly the same number of electrons as a neutral atom of an inert gas. For example either chlorine or potassium, when ionized, has the same number of electrons as neutral argon. Presumably it also has the same structure and differs chiefly in its nuclear charge and therefore in its net charge. So it is assumed that every atom tends to take or lose electrons enough to acquire the structure of a neutral atom of an inert gas, unless it would have to take or lose so many that the electrostatic forces prevent it.

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[1] G. N. Lewis, *J. Amer. Chem. Soc.*, **38**, 762, 1916.

[2] I. Langmuir, *J. Amer. Chem. Soc.*, **41**, 868, 1919.

[3] A. L. Parson, *Smithsonian Misc. Collections*, **65**, No. 11, 1915.

The cases in which the electrostatic forces act in this way are in atoms of low volume, several places removed in the table from any inert gas. Carbon, silicon, iron, and the rare earths are examples of such atoms. In some cases, we may assume that such an atom may still acquire something like the same structure of electrons as an inert gas, but always the next heavier one, not by taking electrons, but by *sharing* them with other atoms. For example, in CO_2, the carbon atom has normally only 6 electrons, and each oxygen atom 8, while the next inert gas, neon, has 10. But if each oxygen atom shares 4 electrons with the carbon, then each atom of either kind has at least a partial claim on 10. This sharing of electrons between atoms, to form structures like the inert gases, is typical of many non-ionized chemical bonds. It is an important fact that they always share an even number, and that almost all molecules made of light elements contain even numbers of electrons.

In many atoms, such as iron and the rare earths, this type of bond can not supply enough electrons to bring the structure up to that of a heavier inert gas; and neither can the atom form a structure like the next lighter inert gas, because the loss of enough electrons for that is electrostatically impossible. So bonds of these atoms are always formed by the loss of a few electrons, and often of a variable number, giving variable valences.

The explanation of this peculiar stability of the inert gas structures given by this theory is based on the fact that the numbers of electrons in their atoms are in the following series:

Helium, $2=2\times(1^2)$
Neon, $10=2\times(1^2+2^2)$
Argon, $18=2\times(1^2+2^2+2^2)$
Krypton, $36=2\times(1^2+2^2+2^2+3^2)$
Xenon, $54=2\times(1^2+2^2+2^2+3^2+3^2)$
Niton, $86=2\times(1^2+2^2+2^2+3^2+3^2+4^2)$

The factor 2 suggests symmetry with respect to a plane, which we may call the "equatorial plane." With this in mind, the other numbers suggest the following geometric structures:

Helium has a single pair of electrons, situated on opposite sides of the nucleus.

Neon has a pair as in helium, surrounded by eight electrons on the corners of a cube.

Argon has a structure like that of neon, with the addition of a second cube surrounding the first. (Langmuir refers to these two cubes as two "layers" of the second "shell," the helium-like pair being the first shell.)

Krypton has a structure like argon, surrounded by a spherical layer of 18 electrons, of which two are at opposite poles of the sphere and the others are all equi-distant from the equatorial plane, eight north and eight south, on equally spaced meridians. (This is the first "layer" of the third "shell.")

Xenon has a structure like krypton, surrounded by a second layer of 18 (the second "layer" of the third "shell.")

Niton has the xenon structure surrounded by a layer of 32.

The symmetry of these layers is obvious, and the way their geometry corresponds with the numbers of elements in the periodic table is most satisfactory.

For the other elements, we may assume that every nucleus has "cells" in space around it, in the positions of all the electrons in the heaviest atom, and many more outside or beyond those. But if all these cells were occupied by electrons, the atom would have such a great negative charge that most of the electrons would be driven away. So in the atom as it exists, the only cells occupied will be a number not very far from enough to make the atom as a whole electrically neutral. This explains, for example, why, in radioactivity, the loss of two positive units from the nucleus as an alpha ray will change an atom of radium from an alkaline earth, like barium, to the inert gas, niton. *Thus the chemical nature of an element will depend entirely on the number of units of positive electricity in the nucleus.*

The tendency of any atom to take or lose electrons is measured by the ease with which, by doing so, it can either complete its outermost layer or lose it entirely. Table I, taken from a paper by Langmuir, gives all the numbers of electrons in the outer layers, and explains readily most of the chemical properties of all the elements.

Another interesting point in connection with this is that Born[1] and Landé,[2] independently of Lewis and Langmuir, arrived at another theory of cubic structure from a study of crystals, but differ in postulating rapid motion of the electrons, which the experimental evidence does not either indicate or positively deny. Whether the rapid motion exists or not is an open question.

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[1] M. Born, *V. d. D. P. G.* **20**, 230, 1918.

[2] A Landé, *V. d. D. P. G.* **21**, 2, 1919; *Zeit. für Physik*, **2**, 380, 1920.

TABLE I

Classification of the Elements according to the Arrangement of the Electrons in their Atoms when Neutral. E = number in Outer Layer.

Completed Layer	$E=0$	1	2	3	4	5	6	7	8	9	10
		H	He								
I	He	Li	Be	B	C	N	O	F	Ne		
II*a*	Ne	Na	Mg	Al	Si	P	S	Cl	A		
II*b*	A	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni
III*a*	Niβ	11 Cu	12 Zn	13 Ga	14 Ge	15 As	16 Se	17 Br	18 Kr		
III*a*	Kr	Rb	Sr	Y	Zr	Cb	Mo	43	Ru	Rh	Pd
III*b*	Pdβ	11 Ag	12 Cd	13 In	14 Sn	15 Sb	16 Te	17 I	18 Xe		
III*b*	Xe	Cs	Ba	La	Ce	Pr	Nd	61	Sa	Eu	Gd
IV*a*		11 Tb	12 Ho	13 Dy	14 Er	15 Tm	16 Tm_2	17 Yb	18 Lu		
IV*a*	14 Erβ	15 Tmβ	16 Tm_2β	17 Ybβ	18 Luβ	19 Ta	20 W	21 75	22 Os	23 Ir	24 Pt
IV*a*	Ptβ	25 Au	26 Hg	27 Tl	28 Pb	29 Bi	30 RaF	31 85	32 Nt		
IV*a*	Nt	87	Ra	Ac	Th	UX_2	U				

So much, then, for the electrons' positions. On the question of what holds them there, or the subject of atomic statics, we have but little evidence. One point, however, that is very suggestive, is the tendency to group in pairs, as illustrated in helium, and in the law that electrons are shared only in pairs. This is strongly suggestive of a set of force doublets, like magnets. So Parson, in a theory worked out independently of Lewis, proposed that the electron itself be considered as a combination of a charge and a circular current, i. e., that it is a charged rotating ring. He showed also that this would give a very strong tendency to form stable cubic groups of 8, like the two layers of the second shell in the Lewis-Langmuir theory. The idea of such a ring-shaped electron is confirmed by the phenomena of the scattering of gamma rays, which have been shown by A. H. Compton[1] to indicate that the electrons are not as small in size as had previously been supposed. They may very likely have diameters of the order of 10^{-10} or 10^{-9} cm. or between a hundredth and a tenth as much as that of the atoms.

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[1] A. H. Compton, *Phys. Rev.* 14, 26, 1919.

To sum up this evidence, we may take it as practically settled that the electrons are in some such positions as those that Lewis and Langmuir suggest, whether they are held there by being magnets, as Parson would have them, or perhaps by motions of the sort described by Born and Landé, or even in some other way.

The Nucleus

The next problem is to get some concrete evidence on the nature of the positive electricity, spoken of above as a "nucleus," and if it is concentrated in a nucleus, to explain why the electrons do not all fall into it, because of the electrostatic attraction. The evidence on the nucleus, so far as it goes, is very definite. The earlier assumption about the positive electricity was that it formed a continuous sphere, of a size equal to that of the atom, with the electrons moving freely through it. But Rutherford,[1] in studying the rebounds of alpha rays from gold leaf, found that the observed distribution of the scattered alpha rays could not be explained on this hypothesis. On the contrary, it could be explained, with considerable accuracy, by the hypothesis that *the positive electricity in each atom is all concentrated in a small massive nucleus, of a diameter of the order of* 10^{-13} *cm. or about* $\frac{1}{100,000}$ *of the diameter of the atom.* Thus a nucleus in an atom is, as Rutherford expressed it, "like a fly in a cathedral." And the "cathedral" itself bears about the same ratio to the smallest particle whose structure we can see that a real cathedral does to the State of Texas.

This evidence is quite conclusive, as noted above, so far as it goes. But just as it was an error to assume that the atom was indivisible and without structure, it would likewise be erroneous to think so of the nucleus. The radioactive transformations all involve breakages of the heavier nuclei. An alpha ray is a helium nucleus, split off and repelled with enormous energy, while a beta ray is an electron, whose great energy shows that it also must come from the nucleus. And Rutherford has recently caused nitrogen and oxygen nuclei to be split by impacts of alpha rays, with the expulsion of particles that may be hydrogen nuclei, and also particles of atomic weight 3, with double charges, that may be an isotope of helium. As an explanation of some of these facts, Harkins[2] has suggested that all nuclei are built up out of hydrogen and helium nuclei, held together electrostatically by electrons placed between them. If so, these nuclear electrons must be contracted to volumes much smaller than they would have outside. But there is no objection to this. Electrons in

[1] E. Rutherford, *Phil. Mag.* 21, 669, 1911; 27, 488, 1914.

[2] W. D. Harkins, *Phys. Rev.* 15, 73, 1920.

different parts of an atom can not safely be assumed to have the same volume. Whether this is so or not, it is at least sure that the nucleus, of anything but hydrogen, small as it is, must have a complicated structure.

Harkins' hypothesis is a form of an old idea known for a hundred years as Prout's hypothesis, and it is indeed plausible, but had long been held false because the atomic weights measured by chemists are not all integers, while any combination of helium nuclei, of weight exactly 4, with hydrogen nuclei, of weight 1.008, ought always to give a nucleus of a weight nearly integral, especially if the pieces are mostly helium. But Aston[1] and Dempster[2] have recently improved Thomson's positive ray analysis to a point where they have separated many of the elements of non-integral atomic weights, such as chlorine and magnesium, into components each of which has an integral weight. Chlorine, for example, has a weight 35.5, and separates into 3 parts of a component of weight 35, to 1 of weight 37. These components are called "isotopes," and are chemically identical, just as the radioactive isotopes are. This chemical identity illustrates the important fact that the "cells" in which the outer electrons lie are independent of the constituents of the nucleus, and the number of them that are filled, as well as the energy relations in filling them, are determined entirely by the total charge of the nucleus.

It has been suggested that this complicated nucleus is held together by purely static forces, but the laws of radioactive disintegration suggest the influence of some process changing with time. Thus the nucleus, like the atom itself, presents a problem of dynamics as well as of structure.

ATOMIC DYNAMICS

Meanwhile the dynamics of the atom itself is by no means well understood. Fifty years ago, or even thirty, there was no problem of atomic dynamics. Newton had long before established his laws of dynamics, that were *the* laws of dynamics. Atoms were supposed to exert repulsions and attractions varying as some inverse powers of the distance, and respond to them according to Newton's laws. Within the atom and around it, even the ether itself was supposed to be governed by these laws, and its particles or component elements, no matter how small they were, or how far removed from direct observation, were supposed to have their accelerations determined by the forces applied to them. There were indeed a few investigators who were disturbed by the fact that "acceleration" could not be measured except relatively, while such a use of Newton's law called for a knowledge of the absolute acceleration of the ether. The ether at least should have been left at rest, to serve as a basis for the measurement of acceleration. But to most students of the subject, Newton's laws and

[1] F. W. Aston, *Phil. Mag.*, 39, 611, 1920.

[2] A. J. Dempster, *Science*, 1921

the idea of absolute acceleration were so familiar that most men failed to doubt them at all, or even consider the shaky foundation on which such a dynamical system for things below the atom rested. This was indeed as true later of those who accepted Einstein's abolition of the ether as of those who did not. Thomson's discovery of electromagnetic mass raised a few doubts on the subject, but only the mysteries of heat radiation and Planck's proposal of the quantum theory sufficed to raise any very serious question of the dynamics of things within the atom. Here the question was of a different sort, on the point of whether things moved continuously or not. But at least it showed the need for some consideration of *atomic dynamics as a subject to be investigated rather than one to be taken for granted.*

In such a subject as this, progress is necessarily slow, because of the impossibility of direct observation of the motions of electrons in an atom. But considerable progress has been made, and we now have a partial insight into atomic dynamics. Planck, in his work on the theory of heat radiation, made it a principle to avoid any assumptions that would introduce unnecessary conflicts with the previously accepted electrodynamics, and so he avoided certain errors made by less cautious investigators. Among the assumptions Planck did make, his most radical one was that a vibrating electron does not ordinarily radiate any energy, as one would expect it to, but that when it does so, it radiates a whole quantum, suddenly. This quantum was an amount of energy $h\nu$, where ν is the frequency of vibration of the light, and h is Planck's constant. This frequency, according to Planck's assumptions, was supposed to be determined by the mass to the electron and the force applied to it, or, if the oscillator was not an electron, it was determined by some pair of quantities corresponding closely to mass and force. Then the magnitude of the quantum was to be determined by the frequency, by the equation $E=h\nu$.

A radical departure from this assumption, and a most important one, was made by Bohr[1], as one of the fundamental hypotheses in his theory of the structure and dynamics of the atom. This theory is a most ingenious one, and has been developed in great detail by Bohr, Sommerfeld and others, and involves many startling assumptions and conclusions which can not be adequately discussed in this brief section. For a more detailed account, the reader is referred to the section of this report by Dr. Page.

The essential point here is that Bohr gave up the idea of a frequency determined by the electron's environment, and a quantum energy determined by the frequency, and assumed exactly the reverse. According to Bohr, the quantum energy was to be determined by the environment, as the energy released when the electron drops from one position in the atom to another, and then the frequency was to be determined, in terms of this energy, by the Planck equation, reversed into the form $\nu=E/h$.

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[1] N. Bohr, *Phil. Mag.*, **27**, 1, 1913.

Planck's assumption was definitely different from the dynamics of bodies of a visible size, but this assumption of Bohr's is obviously much more so. Along with this assumption, Bohr made another, in which the "positions in the atom," from which the electron was to drop, and in which it was to land, were certain orbits of steady motion around the nucleus, like the orbits of the planets around the sun. These orbits themselves were to be fixed by a condition that is mathematically dependent on Planck's quantum constant, h.

By means of this theory, Bohr derived the formula for the Balmer series of the hydrogen spectrum, and a similar series in ionized helium, and Sommerfeld and others applied it to X-ray spectra with a fair degree of success. In many cases, in fact, the agreement with observation is so remarkably exact that, considering spectroscopic data only, it seems difficult to see how the theory can possibly fail to be correct. But in the form in which the theory has usually been stated, the orbits in an atom are all supposed to lie in one plane. In this form it seems impossible to reconcile the theory with the chemical evidence, because a set of orbits in a single plane are so different from the positions where the chemists would put the electrons. If the electrons can be supposed to revolve in small orbits about the corners of the cubes of the Lewis-Langmuir atom, instead of being stationary at these corners, then the theory may perhaps be made to agree with the evidence of chemistry as well as spectroscopy. Such a distribution of orbits has indeed been suggested by Born and Landé, as noted above, in an attempt to explain crystal structures with orbital electrons, but it is not at all certain that this form would agree quantitatively with spectroscopic data, or that it would really satisfy the chemical requirements.

In this connection it is worth noting that the quantitative agreement with spectroscopic data given by the atom with plane orbits is very limited. For atomic hydrogen and ionized helium it is remarkably exact, and it even explains certain complex structures in these lines, especially those discovered by Stark in atoms in a strong electrostatic field. But when it is applied to X-ray series, it demands one arrangement of electrons as a normal atom to explain one set of lines and other arrangements as a normal atom to explain other sets, whereas the sets of lines are so related that the same normal atom ought to explain all the sets. However, if the orbits do exist, but are not actually all in one plane, this inconsistency is to be expected. *The point that is unexpected then is that plane orbits can give such exact quantitative agreement where they do.*

This, in fact, tends to cast some suspicion on quantitative agreements as a sure proof of real truth in a theory. Indeed they are not such sure proof. There have been many mechanical ether theories that have been just as good quantitatively for a certain distance, but no more. And

Fourier's theory of heat conduction in solids gave remarkable quantitative agreements with the facts of temperature distributions within the conducting bodies, although it was based entirely on the assumption that heat was a material substance, "caloric." But this assumption was not necessary. It was merely convenient, in the absence of anything better. And so it may be with Bohr's orbits. The theory of dimensions shows that Fourier's results would follow from any hypothesis on the nature of heat, provided that it recognized certain fundamental empirical laws, and was accompanied by suitable values of the heat conductivity, specific heats and initial temperatures.

In the case of the Bohr theory, its greatest success was in the derivation of Rydberg's constant of spectrum series ν_0, as

$$\nu_0 = \frac{2\pi^2 m e^4}{h^3} = 3.27 \times 10^{15}\ \mathrm{sec}^{-1}$$

where m and e are the mass and charge of an electron, and h is Planck's constant. And its next greatest success has been the explanation of certain doublets in spectrum series, in terms of a certain constant

$$\alpha = \frac{2\pi e^2}{hc} = 7.3 \times 10^{-3}$$

and of the Stark effect in terms of another constant, which we may call

$$S = \frac{3h}{8\pi^2 em}$$

Undoubtedly, these results mean a real connection of these constants with the four fundamental constants m, e, h, and c. The question is, just how much their exact agreement with experimental values can be taken as evidence for the reality of Bohr's atom. The theory of dimensions shows that they must necessarily have the forms

$$\nu_0 = n_1 \frac{me^4}{h^3} f_1 \left(\frac{e^2}{hc}\right)$$

$$\alpha = n_2 f_2 \left(\frac{e^2}{hc}\right)$$

$$S = n_3 \frac{h}{em} f_3 \left(\frac{e^2}{hc}\right)$$

where n_1, n_2, n_3 are pure numbers, presumably not very large nor very small, and f_1, f_2, and f_3 are arbitrary functions. Bohr's theory tells us that $f_1 = f_3 = 1$, and that $f_2(x) = x$, and that the constant numerical coefficients, n_1, n_2 and n_3, then have the values, $n_1 = 2\pi^2$, $n_2 = 2\pi$, $n_3 = \frac{3}{8\pi^2}$. Now if these coefficients had been very unfamiliar numbers, there would be a strong probability that no other theory could be found that would give them. But they are not at all unfamiliar, and if the evidence against Bohr's atom as a reality is very strong, it seems quite reasonable to look elsewhere for the correct explanation of these numbers, and also for the correct explanation of how to use these constants when their values have been found.

This has, in fact, been done recently by Langmuir, who has set up a group of postulates about the forces on an electron in an atom that give the Balmer series and several other results of the Bohr theory from a purely static atom, and also the ionizing potential of helium and heat of dissociation of hydrogen on which Bohr's theory gives incorrect values. It is true, the postulates look somewhat artificial, and some of them are introduced on a frankly empirical basis, being modeled directly on Bohr's theory. But this does not mean that some other justification for them may not be found later, and it illustrates the fact that Bohr's theory, whether true or false, has certainly been of great service in predicting many of the results in question.

One of the strongest arguments in favor of the Bohr theory lies in certain small corrections to the frequencies for hydrogen and ionized helium. These corrections take the form of factors,

$$\frac{1}{1+\frac{m}{M_H}} \quad \text{and} \quad \frac{1}{1+\frac{m}{M_{He}}}$$

respectively, and are ascribed to motions of the nucleus around the stationary center of gravity of the atom. Without them, certain ones of these frequencies would be equal, but with them they should differ by about one part in 2000, and the difference agrees with experiment within the limits of error.

Now the mass of the electron alone might come into the formulas in various ways, either through true motion of the electron, or through the equations of the theory of electromagnetic mass, that connect its mass with its dimensions and internal structure, which may also affect its frequencies. But the mass of the nucleus, appearing in the equations of frequencies of electronic radiation, looks more like sure evidence of motion.

If the nucleus and the electron were held apart by some sort of elastic force, and if the frequencies were given by the ordinary laws of simple harmonic motion, we should have the same fractions entering, but under a radical sign. So the corrections would be only half as large. In Langmuir's theory, the "quantum force," introduced to replace Bohr's centrifugal force, is modified arbitrarily by the factor $\left(1+\frac{m}{M}\right)$. This is one possible solution. Another would be to say that when the electron drops from one position to another, with the center of gravity of the atom fixed, the frequency of the radiation is determined by the work done on the electron alone, and not on the electron and nucleus together. Either assumption is rather arbitrary. But it may be that there is some more reasonable way to obtain this factor. At least it is not utterly impossible to obtain it without orbital motion.

Thus there is much left to be done. But one point at least is fairly certain, namely, the value of Bohr's assumption that the energy to be released as a quantum is determined by some sort of a drop of the electron from one position in the atom to another, and that the frequency of the vibration is determined by the energy released, and not by the position when it vibrates. This hypothesis is confirmed by a considerable mass of data on the excitation of light and of X-rays by the impacts of electrons on atoms. For in such experiments, the energy of the electron making the impact is related to the frequency, sometimes by the quantum law $E=h\nu$, and sometimes by modifications of it, due to the fact that the impacting electron may have to knock a second electron out of the atom, and then the radiation may be emitted by still a third electron falling into the position where the second one was. *In all cases where data are available, both in light and X-rays, the quantum law is confirmed, either in the original or modified form, although in most of them the Bohr orbits have never been worked out satisfactorily, if at all.*

This makes it desirable for many purposes to use the Bohr energy hypothesis by application to a set of empirical positions for electrons, that we may call "energy levels," the use of the word "level" being suggested by the analogy between a drop of the electron toward the nucleus, under electrostatic force, and of a drop of a stone toward the earth, under gravity. Figure 1 gives such a set of energy levels for the internal electrons of a platinum atom, that are concerned in X-ray emission. The energies here are expressed as voltages needed to give those energies to single electrons. In this figure, the top of the diagram represents the highest potential energy, i.e., that of an electron on the outside of the atom, and the lowest line represents the potential energy of an electron at the lowest point it can reach, called the K position, from its close con-

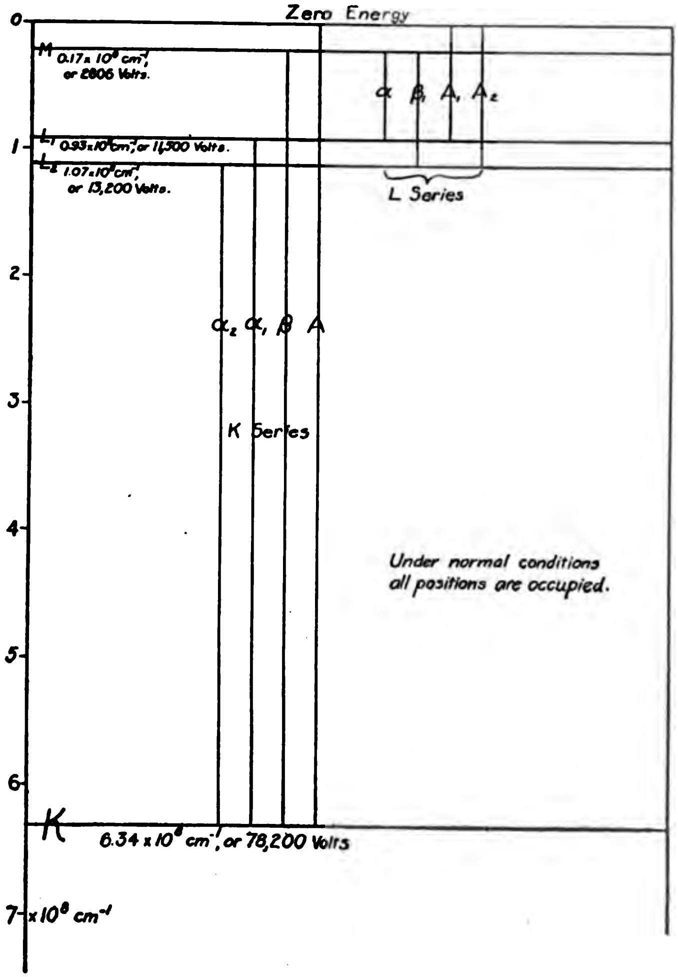
Zero Energy
0
1
2
3
4
5
6
7
M
0.17 x 10⁸ cm⁻¹, or 2806 Volts.
L₁
0.93 x 10⁸ cm⁻¹, or 11,500 Volts.
L₂
1.07 x 10⁸ cm⁻¹, or 13,200 Volts.
α β₁ A₁ A₂
L Series
α₂ α₁ β A
K Series
Under normal conditions all positions are occupied.
K
6.34 x 10⁸ cm⁻¹, or 78,200 Volts
x 10⁸ cm⁻¹

Fig. 1.—Lower energy levels in platinum atom, as obtained from X-ray data. This figure shows only the most important levels, omitting some of the minor ones too near these to be resolved from them on this scale. These are typical of all elements.

nection with the K series of X-rays. The positions used in light emission are all crowded so close together at the top that they can not be drawn on the scale of this diagram. The next diagram, Figure 2, shows on a more enlarged scale the outer positions of electrons in a sodium atom, i.e., the ones concerned in the emission of light; and Figure 3 shows the corresponding positions in the more complex atom of mercury. In all these cases, and many others, a drop from one of these positions to another makes the electron radiate a frequency that depends only on the energy released in the drop, and not on the environment in which the electron finds itself when it lands. For the question of what these positions are, they may be something like Bohr's orbits, or they may be positions of static equilibrium of the electrons, such as the corners of the cubes in the Lewis-Langmuir atom. The chemical evidence would seem to make the latter the more probable.

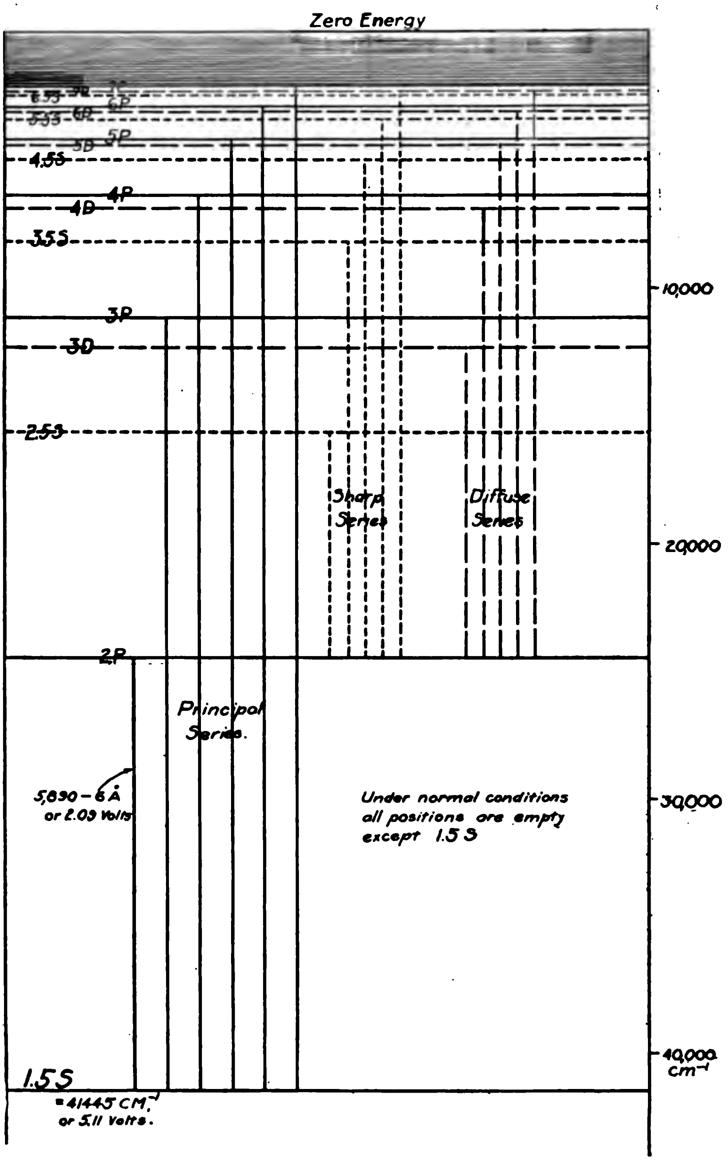

Fig. 2.—Upper energy levels in sodium atom, as obtained from data on light. This type of energy level system is found in all the alkali metals, the P levels all being double.

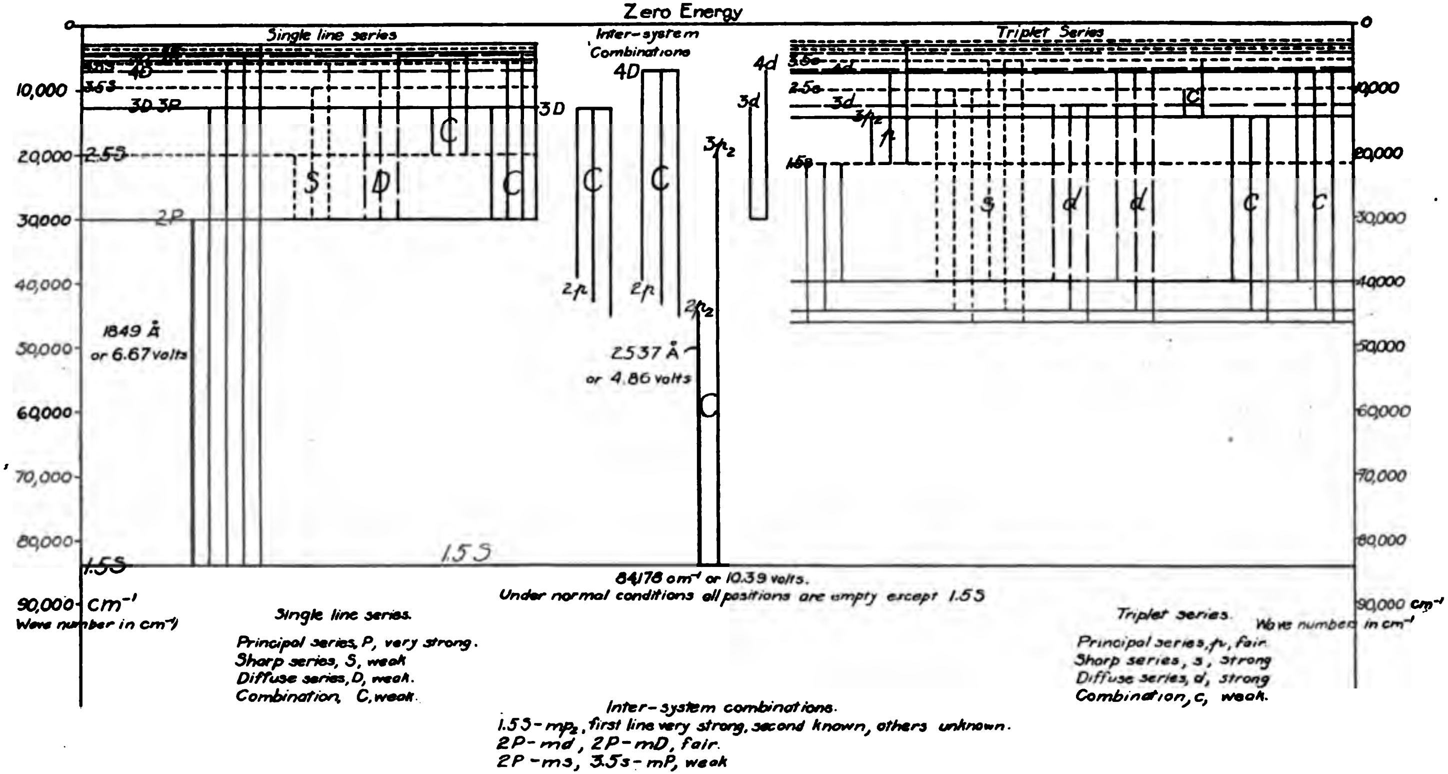

Fig. 3.—Upper energy levels in mercury atom, as obtained from data on light. This type of energy level system is found in all elements of Group II, including the alkaline earths as well as the mercury group.

THE DYNAMICS OF THE ELECTRON

Whatever the energy levels are, the fact that the frequency is determined by the energy released, rather than by the environment, suggests strongly the idea that the electron is not a simple charged sphere, but that, like the nucleus, the electron has a structure and a dynamics of its own. Or, specifically, that it carries in itself a mechanism for maintaining continuous vibrations as long as they are needed to emit the released energy, with a constant frequency, given only by the amount of energy released. And this mechanism must be independent of the environment. It is, for example, just as if the electron was a thin ring, such as Parson assumed, with the charge free to flow on it just as it is on a wireless antenna. In this case, we can readily imagine continuous electrical oscillations on the ring, and we can see how an outside static charge would merely produce a static displacement of the electron's charge, but would not in any way influence its frequency of vibration. The new element in the dynamics of this situation is the law that the frequency is given by the energy released.

However this may happen, this idea of the electron's carrying its own vibratory mechanism fits remarkably well with the available data, not only on the line spectra, but also on the continuous part of the X-ray spectrum, or the "general radiation" as Bragg has called it. For the distribution of this general radiation around the target is most peculiar, and it can be shown to be explained most readily on the assumption that if a cathode ray electron collides with an atom, and releases only a part of its energy for radiation, it may keep the rest as kinetic energy and emit continuous waves while it is traveling along through several atoms. This can be done only if it carries its own mechanism of vibration with it as it moves.[1]

So much for the dynamics of the emission of radiation. The absorption of radiation also brings up some interesting problems. For the frequency that an electron can absorb is often determined by a curious inversion of Bohr's reversed Planck hypothesis, namely, that it will absorb a frequency that will give it a quantum large enough to raise it to some energy level where there is an unoccupied position for it to land in.

Now a man on a crowded stairway can see when a space is open on a step above him, and gather energy enough to step up to it. But if he expends the energy when the space is not open, he not only fails to get there, but also makes trouble for himself in the attempt. The electron apparently has more discretion, and does not try it unless the space is open. Not only that, but if the position is unoccupied but the frequency of the light is wrong, either too large or too small, it again refuses to take a chance to start. And again, if it has been absorbing light for some time, and has absorbed nine-tenths of a quantum, and then is struck by a cathode ray with an energy of one or two-tenths of a quantum, it will not combine the two supplies of energy and make its jump. It demands a full quantum from the cathode ray, or nothing at all, just as though it had not received any energy from the light at all, or had destroyed what it had received. On the other hand, it will sometimes make a jump requiring a whole quantum of energy, when there is every reason to believe it has absorbed but a thousandth of that amount. But, corresponding to that thousandth, only one electron in a thousand will do it. This looks as if, among other unexpected features of the dynamics of electrons, we are to find that *the law of the conservation of energy, which holds absolutely in large bodies, may become only a statistical law as applied to the electron.*

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[1] D. L. Webster, *Bull. Nat. Research Council*, 1, 427, 1920.

And after all, why not? The law of the conservation of energy seems to the physicist most fundamental. But except for theoretical problems on "frictionless" machines, it is not nearly so obvious or important as the law of universal friction and the degradation of energy. And if the degradation of energy becomes statistical at one stage of our analysis, why not its conservation at the next? Of course, as Poincare[1] says, the law of the conservation of energy was suggested by experiment, but can never be definitely overthrown by experiment, because we can always invent some new mathematical function that we can call energy, and define it so as to conserve the total amount of energy in the universe. But at some time or in some place, this may not be worth while. Is not this time the present, and is not this place the interior of the electron?

In this discussion we have used evidence from chemical statics, but have neglected chemical dynamics. But on this point, the dynamics of the electrons, chemical dynamics ought to give some evidence. And indeed it does. It has been known for a long time that a chemical reaction such as the combination of hydrogen and chlorine would proceed at a rate that depends greatly on the temperature and also on the concentrations of the reacting gases. In fact it seems to be fairly well explained by the assumption that the two molecules that collide will react only if they have, taken together, a certain definite amount of energy. Thus the rate of reaction depends on the numbers of collisions per second, which depends on the concentrations. And the rate depends also on the probability that the colliding molecules will have the required energy, which probability increases rapidly with the rising temperature.

So far, so good. But there are certain reactions, called unimolecular reactions, that are decompositions of single molecules. Examples of these are the decomposition of phosphine, PH_3, or phosgene, $COCl_2$, or the dissociation of the vapors of iodine, bromine or chlorine into their component atoms. In these cases, since energy is needed to produce the decomposition, we should expect only the most energetic molecules to decompose. Then we should expect the same rapid increase in the rate of the reaction with rising temperature that we find in any other reaction. And we find it. But we should also expect that the decomposition would occur at collisions between molecules, when the molecules could get the energy needed to decompose them from the energy of their relative motion. This would make the rate depend in a certain way on the concentration. But this prediction fails.

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[1] **H. Poincare, "Science and Hypothesis." Paris, 1901, Chap. VIII.**

This has led several investigators, notably Trautz,[1] Marcelin and Perrin,[3] to assume that the source of energy in such reactions, if not in all reactions, is not molecular collisions, but the absorption of radiant heat or light. This assumption is made especially plausible by a recent proof by Polanyi,[4] and Langmuir,[5] that the collisions, beside making the rate of reaction depend on the concentration in an incorrect way, would also make the rate always too slow, in the case of bromine vapor at least, because *there are never enough collisions with large enough individual energies to supply the energy to the molecules that actually react.* The absorption of radiant heat, on the other hand, would explain the observed sort of dependence on both temperature and concentration exactly. But W. C. M. Lewis,[6] Langmuir, and Polanyi,[7] have each calculated the absolute rate of reaction on this hypothesis, and all find that, while the ratio of the rates at two different temperatures is predicted correctly by the radiation hypothesis, *there never is enough radiant heat present at any temperature to supply the energy to the molecules that actually react.* Polanyi even suggests that since both collisions and radiation fail to supply the energy to the reacting molecules, they must get it by some "new kind of transmission of energy" across empty space.

The fact is, energy seems to disappear from the molecules that are not reacting and to appear suddenly in large amounts, in the few that do react. This is surprisingly similar to the fact that in the absorption of light, energy disappears gradually in the electrons quietly absorbing the light, and appears suddenly, in large amounts, in the ones that either emit light or become photoelectrons. *Thus the evidence of chemical dynamics, as well as that of radiation, suggests that in the dynamics of the electron, the law of the conservation of energy is only statistical.*

[1] M. Trautz, *Z. wiss. Photogr.*, 2, 217, 1916.
[2] R. Marcelin, Thesis, Paris, 1914.
[3] J. Perrin, *Ann. de Phys.*, 11, 5, 1919.
[4] M. Polanyi, *Z. für Physik*, 1, 337, 1920.
[5] I. Langmuir, *J. Amer. Chem. Soc.*, 52, 2190, 1920.
[6] W. C. M. Lewis, *J. Chem. Soc.*, 111, 389, 1917.
[7] M. Polanyi, *Z. für Physik*, 3, 31, 1920.

SUMMARY

To sum up the situation, we have established definitely the existence of electrons and nuclei, and, not quite so definitely, the number of electrons in the atom. With somewhat less certainty, we have the conclusions by Lewis and Langmuir on the positions of the electrons, on the corners of the cubes and the shells of 18 or 32, and Bohr's dynamical law of energy levels. With still less certainty we have the speculations of Parson on the forces holding the electrons in their places, and of Bohr and others on the nature of their energy levels. And going beyond the structure and dynamics of the atom, we have the questions raised by the radioactive data on the structure and dynamics of the nucleus, and by the data of radiation and chemical dynamics on the structure and dynamics of the electron.

PART II

DYNAMICAL THEORIES OF ATOMIC STRUCTURE

BY LEIGH PAGE

Investigation of the properties of cathode rays and of the radiations from radioactive substances have convinced the physicist that the ultimate particles of which matter is constituted are electrically charged. Negatively charged particles, or electrons, can be pulled out of the atom by a variety of methods, such as application of heat, impact of ions, exposure to ultraviolet light or X-rays, or they may be emitted spontaneously by radioactive substances in the form of β rays. It is found, however, that all electrons, no matter from what they come or how they may have been produced, have the same charge and mass. Moreover, the experiments of Kaufmann[1] and Bucherer[2] have indicated that the masses of these negatively electrified particles are entirely electromagnetic, suggesting that the electron consists of nothing more material than negative electricity. Millikan's[3] experiments give for the charge of the electron $4.77\ (10)^{-10}$ E. S. U., and if this number is combined with the value of the ratio of charge to mass obtained from the deflections observed when streams of electrons pass through electric and magnetic fields, the mass of the electron is found to be $9.00\ (10)^{-28}$ gm. This is only one eighteen hundredth part of the mass of an atom of the lightest known element, hydrogen. Electromagnetic theory enables the electron's dimensions to be calculated from the known values of charge and mass, provided its shape and distribution of charge are known. Assuming it to be a uniformly charged spherical shell (Lorentz electron), its radius comes out $1.88\ (10)^{-13}$ cm., which is about a ten-thousandth part of that of the atom. Furthermore, theory shows that the mass m should increase with the velocity of the electron according to the formula

$$m = \frac{m_0}{\sqrt{1-\beta^2}}$$

where the constant m_0 is the rest mass, and β is the ratio of the velocity of the electron to that of light. This formula, which has been verified by the experiments of Bucherer referred to above, is the same as that required by the relativity theory for all masses.

Until recently, the only known instances of expulsion from an atom of positively charged particles have been in the spontaneous emission of α particles by radioactive substances. These particles are helium atoms arrying a charge equal in magnitude to twice the charge on the electron.

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[1] Kaufmann, *Gött. Nachr.*, 143, 1901.

[2] Bucherer, *Phys. Zeit.*, 9, 755, 1908.

[3] Millikan, *Phys. Rev.*, 2, 109. 1913

Of late, however, Rutherford[1] has found that bombardment by high speed α particles drives out of the nitrogen atom singly charged particles having the mass of the hydrogen atom, and expels doubly charged particles of a mass three times as great from the atoms of both nitrogen and oxygen. It is significant, however, that the positively charged particles obtained from atomic disruption have masses of the order of magnitude of those of the hydrogen and helium atoms, and hence very much greater than the mass of the electron.

THE NUCLEUS OF THE ATOM

Since the atom as a whole is electrically neutral, it must contain as much positive as negative electricity. The earliest atomic models based on the electrical theory of matter were proposed by Kelvin[2] and J. J. Thomson.[3] The latter has conceived the atom to consist of a sphere of positive electricity of atomic dimensions, in which electrons are embedded. Assuming that the scattering of β rays is due to close approaches to the electrons in the atom, a theory of scattering was developed, and verified experimentally by Crowther.[4] Moreover, comparison of calculations based on this model with the results of experiments on the scattering of β rays and of X-rays led to the conclusion that the number of electrons in the atom is of the same order of magnitude as the atomic weight.

Thomson's model is particularly attractive in that the simple harmonic force of restitution exerted by the positive electricity on an electron displaced from the center of the atom gives a reason for the sharpness of emission lines appearing in the spectra of gases. A difficulty arises, however, if the mass of the atom is supposed to be entirely electromagnetic. For theory shows the mass to vary inversely with the radius of the charged particle, and as the quite negligible mass of the electron makes it necessary to attribute substantially the entire mass of the atom to the positive electricity which it contains, the radius of the positive sphere should be much less, rather than greater, than that of the electron.

The final overthrow of Thomson's concept of the positive sphere came as the result of Geiger and Marsden's[5] experiments on the single scattering of α rays. The occasional large deflections found when these rays are scattered by passing through very thin metallic foils can be explained only by assuming a very close approach to a small but massive highly charged particle. Hence Rutherford[6] was led to adopt the atomic model previously suggested by Nagaoka,[1] in which the typical atom is supposed to consist of an excessively minute and comparatively massive positively charged nucleus, about which is distributed a number of electrons sufficient to make the atom as a whole electrically neutral. Darwin's[2] calculations showed that in order to explain the dependence of the observed deflections on the velocity of the impinging α rays the inverse square law of force must be assumed to hold to within a distance from the center of the nucleus varying from 2 $(10)^{-13}$ cm. in the case of hydrogen to 4 $(10)^{-12}$ cm. in the case of gold, and comparison of the theoretical formula for scattering with experimental data suggested that the nuclear charge, expressed as a multiple of the electronic charge, is equal to approximately half the atomic weight.

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[1] Rutherford, *Proc. Roy. Soc.*, **97**, 374, 1920.

[2] Kelvin, *Phil. Mag.*, **3**, 257, 1902.

[3] J. J. Thomson, *Phil. Mag.*, **7**, 237, 1904.

[4] Crowther, *Proc. Roy. Soc.*, **84**, 226, 1910.

[5] Geiger & Marsden, *Phil. Mag.*, **25**, 604, 1913.

[6] Rutherford, *Phil. Mag.*, **21**, 669, 1911, and **27**, 488, 1914.

Meanwhile Barkla[3] had shown that the mass absorption coefficients for X-rays passing through air and various metals indicated that the number of electrons in the atom is very nearly half the atomic weight. While his deductions were made on the basis of the theory of J. J. Thomson mentioned above, it was shown later that Rutherford's model of the atom led to the same results.

If hydrogen be excepted, the ordinal numbers specifying the positions of the first twenty elements in the periodic table are very nearly half their respective atomic weights. In fact, a considerable divergence from this ratio exists only in the cases of elements of high atomic weight. The ordinal number corresponding to the place occupied by each element in the periodic table may be termed its *atomic number*, and Van den Broek[4] has suggested that this number is in each case equal to the nuclear charge (expressed in terms of the electronic charge as unity), and therefore also equal to the number of electrons in the portion of the atom outside the nucleus. From this point of view, the essential quantity which determines the position of an element in the periodic table is not its atomic weight, but the magnitude of its nuclear charge. Van den Broek's suggestion was thoroughly confirmed by the important work of Moseley[5] on the X-ray spectra of the elements. Moseley's measurements of the characteristic frequencies of both K and L radiations over a long range of elements showed that the square root of the frequency is very nearly proportional to the atomic number less a constant, and thus provided a very powerful means of determining the proper place in the periodic table of doubtful elements, and of predicting as yet undiscovered ones.

[1] Nagaoka, *Phil. Mag.*, 7, 445, 1904.
[2] Darwin, *Phil. Mag.*, 27, 499, 1914.
[3] Barkla, *Phil. Mag.*, 21, 648, 1911.
[4] Van den Broek, *Phys. Zeit.*, 14, 32, 1913.
[5] Moseley, *Phil. Mag.*, 27, 703, 1914.

The study of the chemical properties of radioactive elements by Soddy[1] and Russell[2] showed that when an α particle is emitted the element's position in the periodic table is shifted two places to the left, whereas the emission of a β ray moves the element one place to the right. On the view that the particles emitted in radioactive transformations come from the nucleus, the explanation is obvious. But the emission of an α particle from the atom must reduce its atomic weight by 4, whereas the emission of a β particle will produce no appreciable alteration in its weight. Now in some instances an α ray change is followed by two changes in which β rays only are emitted. Such a succession of transformations will bring the element back into the place in the periodic table originally occupied, but with an atomic weight diminished by 4. Elements having the same nuclear charge, but differing in atomic weight, are known as *isotopes*. Except for the minute differences in wave lenth of lines in the visible spectrum found by Aronberg[3] and in the infra-red by Loomis,[4] all physical and chemical properties of isotopes not directly connected with mass are found to be identical.

Since the mass of the electron is so much smaller than that of the hydrogen atom, the nucleus must be accountable for practically the entire mass of even the lighter atoms. The chemist's determinations of atomic weight are necessarily statistical, but the positive ray analysis developed by J. J. Thomson has supplied a valuable method of investigating the masses of individual atoms. Essentially this method consists in measuring the ratio of charge to mass of charged atoms by passing them through successive electric and magnetic fields. Aston's[5] experimental measurements indicate that the elements whose atomic weights are whole numbers (on the basis of 16 for oxygen) are pure, while those with fractional weights consist of a mixture of isotopes, each of which has a whole number for its atomic weight. Thus helium, carbon, nitrogen, oxygen are pure, while neon consists of a mixture of atoms of weights 20 and 22, chlorine of the two isotopes 35 and 37, and argon of isotopes 36 and 40. By a similar method Dempster has found isotopes for magnesium having atomic weights 24, 25 and 26, and very recently Harkins has effected a slight separation of the isotopes of chlorine by a diffusion method. These results suggest that all nuclei are built up of singly charged hydrogen nuclei cemented together by electrons, the combination being particularly stable in such a case as the helium nucleus. The atomic weight 1.008 of hydrogen given by the chemists is confirmed by Aston, and it is suggested that this slight divergence from the whole number rule is due to the effect on the heavier atoms of the mutual masses of their constituents. Harkins[1] has made a study of the relative abundance of the elements occurring in meteorites and on the earth's surface, and finds that those whose atomic weights are integral multiples of four occur in by far the greatest quantities. This group of elements he calls the helium series, as the atom of each may be considered to have a nucleus consisting of helium nuclei cemented together by nuclear electrons. The other elements, whose nuclei must contain hydrogen nuclei as well as helium nuclei and cementing electrons, are far less abundant, and hence presumably less stable. The fact that the radioactive elements emit helium nuclei in the form of α rays, but never hydrogen nuclei or in fact any other positively charged particles, is excellent evidence of the extreme stability of the helium nucleus and of its existence *per se* as a constituent of the nuclei of heavier atoms. However, Rutherford's[2] discovery of the expulsion of particles of atomic weight 3 from oxygen (16) under bombardment by α-rays, suggests that these particles are an integral constituent of the oxygen nucleus. Therefore, against Harkins' hypothesis that the oxygen nucleus consists of four helium nuclei, Rutherford considers the nucleus of this atom to be composed of one helium nucleus and four doubly charged particles of weight 3 cemented together by two electrons. This nuclear model has an advantage over Harkins' in that electrons are provided to bind together the positively charged particles. Furthermore, the emission of hydrogen nuclei as well as particles of weight 3 from nitrogen (14) lends support to the view that the nucleus of that element contains four doubly charged particles of weight 3, two hydrogen nuclei, and three binding electrons. Similarly the carbon nucleus (12) may consist of four weight 3 particles and two cementing electrons.

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[1] Soddy, *Chem. News*, 107, 97, 1913.
[2] Russell, *Chem. News*, 107, 49, 1913.
[3] Aronberg, *Astro Phys. Jour.*, 47, 96, 1918.
[4] Loomis, *Astro Phys. Jour.*, 52, 248, 1920.
[5] Aston, *Phil. Mag.*, 39, 611, 1920.

Although practically the entire mass of the atom is associated with the nucleus, all but a minute portion of the atom's volume lies outside it. In this outer atom must be present normally a number of electrons sufficient to neutralize the nuclear charge. While the mass of the atom and the phenomena of radioactivity are determined almost entirely by the nature of the nucleus, its other physical and chemical properties are practically independent of the structure of this central core. In dealing with the emission of radiation, or with chemical valency, for instance, the arrangement and motions of the outer electrons are the determining factors. The nucleus is relatively so compact that it may be considered as a point charge. The magnitude of its charge is vital, but its structure is inconsequential. What little is known or surmised regarding the atomic nucleus has already been briefly outlined; the remainder of this report will be devoted to a discussion of the outer atom.

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[1] Harkins, *Phys Rev.* **15**, 73, 1920.
[2] *Proc. Roy. Soc.*, **97**, 374, 1920.

QUANTUM THEORY OF LINE SPECTRA

Attempts to formulate a strucure for the outer atom have proceeded in general along two lines—the first based on spectroscopic, the second on chemical evidence. Theories of the first type are dynamical in nature, and have usually postulated revolution about the nucleus of electrons evenly spaced in rings. Of several such dynamical theories which have been proposed, the only one which has attained considerable success is that based on the energy quantum used by Planck[1] in deriving the law of black radiation. On the other hand, the most successful theories which have been proposed to explain the chemical properties of the elements—in particular valency—seem to require an arrangement of the electrons which is statical in the sense that each electron, though it may be in motion, is confined to a small portion of the space occupied by the atom.

The quantum theory of the line spectra of the elements, suggested by Nicholson's[2] attempt to account for certain lines in the spectra of stellar nebulae and the solar corona, was proposed by Bohr[3] in 1913, and has been considerably extended since by Bohr, W. Wilson,[4] Schwartzschild,[5] Epstein[6] and Sommerfeld.[7] The first postulate of the theory is that under normal conditions each electron revolves about the nucleus in an orbit of invariable form without radiating or absorbing energy. These orbits are determined by the following conditions:

(a) The impressed force on the electron is that calculated on electromagnetic theory from the strength of the electric and magnetic fields in which the electron under consideration is moving. In order of intensity these fields are (1) the electrostatic field produced by the comparatively stationary nucleus, (2) the electric and magnetic fields due to other electrons in the atom, (3) electric fields due to external sources as in the Stark effect, (4) magnetic fields due to external sources as in the Zeeman effect. The kinetic reaction of the electron is supposed to consist only of the term containing the product of mass by acceleration, since the assumption that no energy is radiated requires that the usual term expressing the radiation reaction should be rejected. This is a very serious contradiction of the classical electrodynamics, which leads to radiation of energy and its consequent reaction whenever an electron is accelerated, no matter what assumptions may be made regarding the shape of the electron or the distribution of charge on it. This inconsistency is in no wise made less by the fact that Sommerfeld retains the variable transverse and longitudinal masses which the same electromagnetic equations lead to, and that Rubinowicz makes use of these equations to calculate the angular momentum of the emitted radiation.

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[1] Planck, "Theory of Heat Radiation" (Trans. by Masius), 1914.

[2] Nicholson, *Month. Not. Roy. Astron. Soc.*, **72**, 49, 1912.

[3] Bohr, *Phil. Mag.*, **27**, 1, 1913, et seq.

[4] W. Wilson, *Phil. Mag.*, **29**, 795, 1915.

[5] Schwarzschild, *Sitz. Berl. Akad.*, 548, 1916.

[6] Epstein, *Ann. d. Phys.* **50**, 489, 1916, *et seq.*

[7] Sommerfeld, *Ann. d. Phys.* **51**, 1, 1916, *et seq.*, and "Atombau und Spektrallinien," Braunschweig, 1921.

(b) The classical dynamics alone would make possible an infinite number of orbits in any given finite region around the nucleus. Of these a limited number are selected by the following condition. Let the electron have k degrees of freedom, and let q_i and p_i be the generalized coördinate and momentum respectively corresponding to the ith of these. In the case of revolution in a circle, for instance, q is the angle turned through, and p the moment of momentum.[1] Then only those orbits are possible for which

$$\oint p_i\,d\,q_i = n_i\,h, \qquad i = 1, 2, 3 \ldots k, \tag{1}$$

where the integral is taken all the way around the orbit, n_i is an integer, and h ($6.54(10)^{-27}$ ergs sec) is Planck's constant. The essence of this postulate lies in the concept of a limited number of stable orbits, differing from one another in energy by definite steps.

The first postulate of the Bohr-Sommerfeld theory determines the stationary orbits in the non-radiating atom. The law of conservation of energy requires that radiation should take place when an electron falls

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[1] In general, if the kinetic energy T is expressed as a function of the generalized coördinates q and the corresponding velocities $\dot{q}$,

$$p_i = \frac{\partial T}{\partial \dot{q}_i}$$

In terms of the polar coördinates r and θ, for instance,

$$T = \frac{m}{2}(\dot{r}^2 + r^2\dot{\theta}^2)$$

and

$$p_\theta = \frac{\partial T}{\partial \dot{\theta}} = mr^2\dot{\theta}$$

$$p = \frac{\partial T}{\partial \dot{r}} = m\dot{r}$$

from an orbit of greater energy U_o to one of less energy U_i. The second postulate of the theory states that the energy radiated is equal to $h\nu$, where ν is the frequency of the emitted radiation. Hence this frequency may be calculated from the formula

$$h\nu = U_o - U_i \tag{2}$$

It must be noted, however, that U_o and U_i do not represent the energies of the radiating electron alone in its initial and final states, but rather the internal energies of the whole atom in these two configurations. Thus when an electron leaves an orbit in which other electrons are present, the alteration in the energy of the electrons remaining in the orbit must be taken into account.

On the basis of this theory the problem of atomic structure consists in building up each atom in such a way that the passage of an electron from one stationary state to another will give calculated frequencies in agreement with those observed by the spectroscopist. The simplest types of atom are those in which the number of electrons in the atom is least, and it is for these that the theory has been most successful. In fact the most precise confirmation of the theory exists in the case of atoms in which only a single electron is present, such as the hydrogen atom and the helium atom which has lost one electron.

The nuclear charge is equal to Ze for an element of atomic number Z, if e denotes the charge on the electron. Hence if only a single electron of mass m is present in the atom, and if this electron is revolving around the nucleus with angular velocity ω in a circle of radius a,

$$\frac{e^2Z}{a^2} = ma\omega^2 \tag{3}$$

The quantum condition (1) gives

$$2\pi ma^2\omega = nh \tag{4}$$

From these two equations it follows that

$$\begin{aligned} a &= \left(\frac{h^2}{4\pi^2me^2}\right)\frac{n^2}{Z} \\ &= 0.532\ (10)^{-8}\frac{n^2}{Z}\ \text{cm} \end{aligned} \tag{5}$$

and the ratio of the velocity of the electron to that of light is

$$\beta = \frac{a\omega}{c}$$

$$=\left(\frac{2\pi e^2}{hc}\right)\frac{Z}{n}$$

$$\equiv \alpha\frac{Z}{n}$$

$$=7.29\,(10)^{-3}\frac{Z}{n} \qquad (6)$$

Expression (5) shows that the radii of successive stationary orbits are in the radio of 1:4:9:16, etc., for any one atom, while for a given value of n the radius varies inversely with the atomic number Z. The numerical value of the radius is evidently of the order of magnitude to be expected from other estimates of atomic dimensions.

Equation (6) shows that the velocity of the revolving electron is greatest in the first orbit, and increases with the atomic number. From the numerical value of the velocity it is evident that the increase of mass with velocity becomes appreciable in the inner orbits of elements of high atomic number. Sommerfeld's chief contribution to the theory has been the calculation of the effects due to this variable mass.

The angular velocity ω is obtained by eliminating a from (3) and (4). It is seen to be

$$\omega=\frac{8\pi^3 me^4}{h^3}\,\frac{Z^2}{n^3},$$

$$=4.12\,(10)^{16}\frac{Z^2}{n^3}\text{ per sec.}$$

The energy of an electron in the nth quantum orbit consists of the potential energy

$$V=-\frac{e^2Z}{a}$$

and the kinetic energy

$$T=\tfrac{1}{2}\,ma^2\omega^2$$

$$=\frac{e^2Z}{2a}$$

Adding, the total energy is

$$U=-\frac{e^2Z}{2a}$$

$$=-\left(\frac{2\pi^2 me^4}{h^2}\right)\frac{Z^2}{n^2} \qquad (7)$$

Therefore, when an electron passes from an outer to an inner orbit, the second postulate of the quantum theory gives for the frequency of the emitted radiation

$$\nu = \left(\frac{2\pi^2 me^4}{h^3}\right) Z^2 \left(\frac{1}{n_i^2} - \frac{1}{n_o^2}\right).$$

Now, when their numerical values are substituted for the quantities in the first parenthesis, this expression is found to have the value of Rydberg's constant N_∞ [3.29(10)^{15} per sec] to the degree of accuracy to which the values of e, m and h are known.

Hence, the above expression reduces to

$$\nu = N_\infty Z^2 \left(\frac{1}{n_i^2} - \frac{1}{n_o^2}\right) \tag{8}$$

which, for Z equal to unity, has the form of Balmer's well known formula for the hydrogen series. It is this remarkable numerical agreement which has forced physicists to attach so much weight to Bohr's theory.

Bohr has given an interesting comparison of the frequency ν of the emitted radiation with the frequencies ν_i and ν_o of the electron in its inner and outer orbits. It follows at once from (5) and (6) that

$$\nu_i = 2\,\mathrm{N}_\infty \frac{Z^2}{n_i^3}$$

and a similar expression for ν_o. As n_o is always greater than n_i, put

$$n_o = n_i + \rho$$

where ρ is a positive integer. Then

$$\frac{\nu}{\nu_i} = \frac{n_i}{2}\left(1 - \frac{n_i^2}{n_o^2}\right) = \rho \left(\frac{1 + \frac{\rho}{2n_i}}{1 + \frac{\rho}{n_i}}\right)\left(\frac{1}{1 + \frac{\rho}{n_i}}\right)$$

which is less than unity for all ρ's if $n_i \leqq 2$, and for all n_i's if $\rho = 1$. Therefore the frequency of the radiation emitted is less than the frequency of revolution in the inner orbit if the electron falls into either the first or the second Bohr ring, no matter from what ring it may have come; and this relation is also true when the electron falls from one ring to the next inside, no matter what the quantum numbers of these two rings may be. If these conditions are not satisfied, however, the frequency of the radiation may be greater than that of revolution in the inner orbit.

Similarly

$$\frac{\nu}{\nu_o} = \frac{n_o}{2}\left(\frac{n_o^2}{n_i^2} - 1\right) = \rho\left(1 + \frac{\rho}{2\,n_i}\right)\left(1 + \frac{\rho}{n_i}\right)$$

is always greater than unity. Therefore the frequency of the emitted radiation is always greater than the frequency of revolution in the outer orbit.

Provided ρ is one, the expressions for $\frac{\nu}{\nu_i}$ and $\frac{\nu}{\nu_o}$ both converge to unity as n_i increases. Therefore the frequency of the radiation emitted when an electron falls from one orbit to the next inner orbit approaches the frequency of revolution as the quantum numbers of the orbits increase.

It may be noted in passing that Planck's theory of the linear oscillator differs from Bohr's theory in that the former assumes the frequency of the emitted radiation to be the same as the frequency of oscillation in all cases. However, Einstein[1] has shown that Planck's radiation formula may be deduced from hypotheses practically identical with those underlying Bohr's theory of atomic structure.

Hydrogen and Similar Elements

As the atomic number Z of hydrogen is one,

$$\nu = N_\infty\left(\frac{1}{n_i^2} - \frac{1}{n_o^2}\right) \tag{9}$$

A series is obtained when n_i remains constant, and n_o takes on various integral values. Thus if an electron falls into the second ring from the third, fourth, fifth, or sixth, the lines obtained are the $H\alpha$, $H\beta$, $H\gamma$ or $H\delta$ of the Balmer series. If it falls into the first ring from an outer ring, one of the lines of the Lyman ultraviolet series is produced, while if it falls into the third ring, one of the lines in the infrared series discovered by Paschen is given forth. While it is generally assumed that the various orbits under consideration lie in the same plane, this hypothesis is not essential.

The elementary theory presented above is based on the assumption that the mass of the nucleus is so much greater than that of the electron that the former remains practically stationary. A more exact investigation takes into account the motion of both nucleus and electron about their common center of gravity. If M stands for the mass of the nucleus and A for the radius of the circle which it describes about the center of gravity of the atom, equation (3) must be replaced by

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[1] Einstein, *Deut. Phys. Ges.* 318, 1916.

$$\frac{e^2 Z}{(a+A)^2} = ma\omega^2 = MA\omega^2 \tag{3'}$$

and the quantum condition (4) by

$$2\pi(ma^2 + MA^2)\,\omega = nh \tag{4'}$$

If now

$$\frac{1}{\mu} \equiv \frac{1}{M} + \frac{1}{m}$$

expression (7) for the energy of the atom becomes

$$U = -\left(\frac{2\pi^2 \mu e^4}{h^2}\right)\frac{Z^2}{n^2} \tag{7'}$$

and the constant N_∞ in (8) must be replaced by

$$\begin{aligned} N_H &= \frac{\mu}{m} N_\infty \\ &= \frac{N_\infty}{1 + \dfrac{m}{M_H}} \end{aligned} \tag{10}$$

It should be noted here that the energy U is that of the *entire* atom—nucleus and electron together— and that the whole number of quanta of angular momentum are not associated entirely with the revolving electron, but divided between electron and nucleus.

Consider a helium atom which has lost one electron. As the atomic number of helium is two, the remaining electron will radiate energy as it falls inwards according to the law

$$\nu = 4\,N_{He}\left(\frac{1}{n_i^2} - \frac{1}{n_o^2}\right) \tag{11}$$

The series longest known is that for which $n_i = 4$ and n_o takes on the values 5, 6, 7, etc. In this case (11) may be split up into the two formulae,

$$\nu = N_{He}\left(\frac{1}{4} - \frac{1}{m^2}\right) \qquad m \equiv \frac{n_o}{2},\ n_o \text{ even}$$

and

$$\nu = N_{He}\left(\frac{1}{4} - \frac{1}{(m + \frac{1}{2})^2}\right) \qquad m \equiv \frac{n_o - 1}{2},\ n_o \text{ odd}$$

which were supposed to represent separate series until Bohr showed that they belong together. The first differs from the Balmer series for hydrogen only in the value of the Rydberg constant. The second is the series known at first as the Pickering series of hydrogen.

Now, as the atomic mass of helium is 4,

$$N_{He} = \frac{N_\infty}{1 + \dfrac{m}{4\,M_H}}$$

or, comparing with (10),

$$\frac{M_H}{m} = \frac{N_H - \frac{1}{4} N_{He}}{N_{He} - N_H}$$

Paschen finds

$$N_H = 109{,}677.691c$$

$$N_{He} = 109{,}722.144c$$

where c is the velocity of light, from which it follows that[1]

$$\frac{M_H}{m} = 1846.9$$

which is in excellent agreement with the ratio of the mass of the hydrogen atom to that of the electron as found by other methods. The value of N_∞ is found to be

$$N_\infty = 109{,}737.11c$$

Moreover, as

$$\frac{M_H}{m} = \frac{\dfrac{e}{m}}{\dfrac{e}{M_H}} = \frac{\dfrac{e}{m}}{96{,}494 \text{ coulombs}}$$

it follows that

$$\frac{e}{m} = 1.7686\,(10)^7 c$$

This value of the ratio of charge to mass not only agrees excellently with values obtained by other methods, but, on account of the high precision of spectroscopic measurements, it is probably more accurate than any other determination.

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[1] To obtain exactly this value of $\frac{M_H}{m}$ and the value of $\frac{e}{m}$ below, account must be taken of the fact that the atomic weight of hydrogen is not 1 but 1.008.

In addition to the one discussed above, two other series are known for ionized helium. One of these, first observed by Fowler in 1912, has a value of n_i equal to 3, and the other, found by Lyman in 1919, lies in the ultraviolet with a value of n_i equal to 2.

In a lithium atom which has lost two electrons, $Z=3$, and series lines would be expected to satisfy the relation

$$\nu = 9N_{Li}\left(\frac{1}{n_i^2} - \frac{1}{n_o^2}\right)$$

$$= N_{Li}\left(\frac{1}{\left(\frac{n_i}{3}\right)^2} - \frac{1}{\left(\frac{n_o}{3}\right)^2}\right) \qquad (12)$$

While such lines have not been observed in spectra produced in the laboratory, it has been suggested that they may correspond to certain lines emitted by nebulae of the Wolf-Rayet type.

X-Ray Spectra

In the case of elements of higher atomic number than those considered above, no available external field would be strong enough to remove all of the electrons save one from the atom. Consequently it is necessary to consider atoms in which a number of electrons are present. In such cases the forces of repulsion on an electron due to other electrons in the atom must be taken into account as well as the force of attraction toward the nucleus. If p electrons are evenly spaced on a circle of radius a at the center of which the nucleus is located, the net central force on each electron is found by a simple calculation to be

$$\frac{Ze^2}{a^2} - \frac{e^2}{4a^2}\sum_n \csc\frac{\pi n}{p}, \quad n=1, 2 \cdots p-1 \qquad (13)$$

The quantity

$$S_p = \frac{1}{4}\sum_n \csc\frac{\pi n}{p}$$

is known as the *nuclear defect* of the ring, and the *effective atomic number* Z' is obtained by subtracting the nuclear defect from the atomic number Z.

Consider a number of electrons evenly spaced in a circular ring, each of which has two quanta of angular momentum. If electrons having one quantum of momentum each are present on an inner ring, the distance of each of them from the nucleus will be less (on account of the nuclear defect of the inner ring) than one quarter of the radius of the two-quanta ring. Hence, with a fair degree of approximation, they may be considered as concentrated at the nucleus itself in so far as their effect on the motion of electrons in the two-quanta ring is concerned. Therefore the nuclear defect due to electrons on inner rings may be considered as equal to the number of electrons present in these rings. Similarly the nuclear defect (negative) due to electrons on outer rings may be neglected.

The Kα lines of the X-ray spectra are supposed to be produced by an electron falling from the two-quanta or *L* ring into the one-quantum or *K* ring. Since the velocity of an electron in the *K* ring becomes comparable to that of light as the atomic number increases, the variation of its mass with velocity must be taken into account.

Assume p electrons in the *K* ring, and q in the *L* ring under normal conditions. Let one electron be removed from the *K* ring to the surface or outside the atom. Then the *K* ring will contain $p-1$ electrons. If now one of the q electrons in the *L* ring falls into the *K* ring the *Kα* line is emitted.

As before, stationary orbits are determined by the conditions (3) and (4), except that Z must be replaced by the effective atomic number Z', and

$$m=\frac{m_0}{\sqrt{1-\beta^2}}$$

where m_0 is the rest mass. The kinetic energy is that of the relativity theory, namely

$$T=mc^2$$

so that the total energy of an electron becomes

$$U=\frac{e^2Z'}{a}\left(\frac{1-\beta^2}{\beta^2}\right)$$

Substituting the value of a from (5)

$$U=\left(\frac{4\pi^2me^4}{h^2}\right)\left(\frac{1-\beta^2}{\beta^2}\right)\frac{Z'^2}{n^2}$$

$$=\left(\frac{4\pi^2m_0e^4}{h^2}\right)\frac{\sqrt{1-\beta^2}}{\beta^2}\,\frac{Z'^2}{n^2}$$

and putting for β the value given by (6),

$$\frac{U}{Nh}=\frac{2}{\alpha^2}\sqrt{1-\frac{\alpha^2}{n^2}Z'^2} \tag{14}$$

for each electron. For the $p-1$ electrons in the K ring and q electrons in the L ring in the initial configuration,

$$\frac{U_1}{Nh}=\frac{2}{\alpha^2}\left[(p-1)\sqrt{1-\frac{\alpha^2}{1^2}(Z-S_{p-1})^2}+q\sqrt{1-\frac{\alpha^2}{2^2}(Z-p+1-S_q)^2}\right]$$

and for the p electrons in the K ring and $q-1$ electrons in the L ring in the final configuration,

$$\frac{U_2}{Nh}=\frac{2}{\alpha^2}\left[p\sqrt{1-\frac{\alpha^2}{1^2}(Z-S_p)^2}+(q-1)\sqrt{1-\frac{\alpha^2}{2^2}(Z-\mathrm{p}-S_{q-1})^2}\right]$$

By the second postulate of the quantum theory the frequency of the $K\alpha$ line is given by

$$\frac{\nu}{N}=\frac{U_1}{Nh}-\frac{U_2}{Nh} \qquad (15)$$

Kroo[1] finds the best agreement with experiment when p is taken equal to 3 and q equal to 9. A change in the value of q by a unit or two does not affect the calculated frequency materially, but any change in p leads to results differing radically from those observed experimentally.

If (15) is developed in ascending powers of Z for Kroo's values of p and q, the following expression is obtained,

$$\frac{\nu}{N}=4.48+.75014\,Z^2+1.250\,(10)^{-5}Z^4+1.74\,(10)^{-10}Z^6\ldots$$
$$-1.7221\,Z-6.05\,(10)^{-5}Z^3-13\,(10)^{-10}Z^5\ldots. \qquad (16).$$

Below is given a table of calculated and observed frequencies. The agreement is seen to be excellent.

Z	$\frac{\nu}{N}$ exp.	$\frac{\nu}{N}$ calc.
11	76.25	76.4
15	147.7	147.8
20	271.86	271.6
25	435.4	434.2
30	636.42	636.5
35	880.5	879.5
40	1156	1164
45	1482	1493
50	1871	1866
55	2289	2287
60	2761	2758

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[1] Kroo, *Phys. Zeit.* 19, 307, 1918.

The K lines of shorter wave length are supposed to be due to the passage of an electron from the 3 quanta (M) ring, or 4 quanta (N) ring, to the K ring. The L lines are due to an electron falling into the 2 quanta (L) ring from outer rings. In none of these cases, however, have atomic structures been devised which lead to calculated frequencies agreeing with the experimental values with anything like the degree of precision obtained by Kroo for the $K\alpha$ lines. The difficulty may be due to the fact that attempts to extend the theory to these outer rings have generally been based on the assumption that all the rings lie in the same plane, whereas it seems certain that atomic structure is three dimensional rather than planar. Moreover, it should be noted that Kroo's theory fails to take into consideration the magnetic forces between electrons, which lead to terms of the same order of magnitude as those involved in the relativity mass correction.

It is unfortunate that Kroo's theory of the $K\alpha$ line requires that the numbers of electrons in the K and L rings should be 3 and 9, for the chemical evidence summarized in the periodic table makes it far more probable that the inner ring of the atom contains 2 electrons and the second ring 8. If the elements in this table are arranged so that an inert gas comes at the end of each row, the numbers of elements in successive rows are given by the terms of the series

$$S=2(1^2+2^2+2^2+3^2+3^2+4^2+\ldots)$$

Spectroscopic evidence to be presented later indicates that the number of electrons which may be present in a given ring is definitely limited, and therefore when a ring is saturated the addition of further electrons to the atom results in the formation of a new ring of greater radius. Such a ring is capable of continued existence, however, only when all inner rings have been filled to capacity. Now the inert gases would be expected to be the elements whose outer rings are completely saturated. Thus the periodic table indicates that the numbers of electrons necessary to saturate successive rings are (proceeding outward from the center of the atom) 2, 8, 8, 18, 18 and 32. This evidence against Kroo's numbers 3 and 9 is so weighty that it is doubtful if the excellent agreement between his calculations and the observed X-ray frequencies can be considered as more than accidental. His results do seem to show, however, that the structure of the inner rings is the same for all elements, and that the variation of mass with velocity must be taken into account in computing the energy of a stable orbit.

Applying the second postulate of the quantum theory to absorption, Duane[1] has calculated the K critical absorption frequencies—that is, the lowest frequency of X-radiation necessary to pull an electron in the K ring completely out of the atom—for atomic models containing 2 and 8 electrons in the first and second rings. The following table is taken from his paper.

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[1] Duane, *Science*, 51, 507, 1920.

Z	$\frac{\nu}{N}$ exp.	$\frac{\nu}{N}$ calc.
13	114.8	118.5
15	158.4	163.9
25	482.8	500.8
35	993.6	1000.0
45	1711.0	1717.0
55	2648.0	2643.0
65	3803.0	3812.0
74	5109.0	5118.0

The calculated values are corrected for the influence of one ring on another, as well as for the variation of mass with velocity. While the agreement is not as close as in Kroo's calculations of emission lines, it is nevertheless very significant.

The evidence contained in the periodic table has been interpreted above in terms of the plane atomic model. The evidence in favor of a three dimensional structure of all but the very lightest atoms is so great, however, that the use of the word "rings" in connection with the periodic table must not be considered as more than a manner of speech. The important thing about the Bohr-Summerfeld theory is that it brings out the fact that an electron is stable only in certain stationary states, and that the frequency of the energy radiated or absorbed when it passes from one of these states to another is determined by the second postulate of the theory. In the heavier and hence more complex atoms these states undoubtedly have a spatial distribution, rather than being confined to a plane.

Elliptic Orbits

So far electronic orbits inside the atom have been assumed to be circular. As the central force obeys the inverse square law, however, elliptic orbits as well would be expected, just as in the case of planetary motion. While there is only one degree of freedom in the case of circular orbits in a plane, there are two in the case of elliptic orbits. The generalized coördinates corresponding to these are the azimuthal angle ϕ and the radius vector r. The simple case where the variation of mass with velocity is neglected will be treated first, following the elegant method of separation of variables used by Sommerfeld.[1]

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[1] The dynamical justification for this method of separation of variables is given in Appendix 8 to Sommerfeld's book, and also in E. P. Adams' "The Quantum Theory", *Bulletin of the National Research Council*, Number 5, p. 324.

Writing down the expression for the energy of the revolving electron in terms of the generalized coördinates ϕ and r, and the generalized momenta p_ϕ (moment of momentum) and p_r (radial momentum),

$$U=T+V$$

$$=\frac{1}{2m}\left(p_r^2+\frac{1}{r^2}p_\phi^2\right)-\frac{e^2Z'}{r},$$

which admits of separation of the variables as is evident if we re-write the equation in the form

$$r^2\left[p_r^2-\frac{2me^2Z'}{r}-2mU\right]=-p_\phi^2.$$

Placing each side of this equation equal to the constant $-p^2$

$$p_\phi=p,$$

$$p_r=\sqrt{2mU+2\frac{me^2Z'}{r}-\frac{p^2}{r^2}}.$$

Applying the quantum conditions

$$\S^1 p\,d\phi=nh$$

$$\S\sqrt{2mU+2\frac{me^2Z'}{r}-\frac{p^2}{r^2}}\,dr=n'h$$

where n and n' refer respectively to the azimuthal and radial motions.

The integration of the first of these equations is obvious. The second is integrated most easily by using complex variables, as explained in an appendix to Sommerfeld's book.[1] The results are

$$2\pi p=nh,$$

$$2\pi i\frac{me^2Z'}{\sqrt{2mU}}-2\pi p=n'h,$$

where $i\equiv\sqrt{-1}$.

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[1] "Atombau and Spektrallinien," 2d Ed., p. 476.

Eliminating p

$$\frac{U}{Nh} = -\frac{Z'^2}{(n+n')^2}, \tag{17}$$

from which we find, on applying the second postulate of the quantum theory,

$$\frac{\nu}{N} = Z'^2\left(\frac{1}{(n_i+n'_i)^2} - \frac{1}{(n_o+n'_o)^2}\right) \tag{18}$$

As n and n' are each integers, this formula is indistinguishable from the simple Balmer formula (8). However, in view of the fact that elliptical orbits do not lead to quite the same results as circular orbits when the variation of mass with velocity is taken into account, it is of interest to examine the possibilities involved in (17).

If $n+n'=1$, the only orbit possible is that for which $n=1$, $n'=0$; for $n=0$, $n'=1$ would mean that the vibrating electron executes linear oscillations, which are excluded on account of the fact that it would run into the nucleus in the course of its motion. Therefore elliptical orbits are impossible in the first quantum ring.

In the second ring, $n+n'=2$, and the possibilities are $n=2$, $n'=0$; and $n=1$, $n'=1$. In general, the number of possibilities is equal to the number of quanta $n+n'$ associated with the orbit. The semi-major axis of an elliptical orbit is equal in each case to the radius a of the circular orbit involving the same number of quanta, but as the nucleus is at one focus of the former, the perihelion distance r_{min} is much less than a. This raises the question as to whether electrons moving in elliptic orbits cross the coplanar orbits of other electrons moving in circular paths with which a smaller number of quanta are associated. In order to preserve a reasonable degree of symmetry, it will be assumed that when one electron in a ring moves in an elliptic orbit all other electrons in the same ring do likewise; that these coplanar ellipses are so spaced around the nucleus that the major axes of the orbits of adjacent electrons make equal angles with one another; and that the electrons themselves are in phase. Therefore at any one instant all the electrons in a ring are evenly spaced along the circumference of a circle at the center of which lies the nucleus. Hence the resultant force on any one electron—taking into account the repulsion of other electrons in the same ring as well as the attraction of the nucleus—is always directed toward the nucleus.

Now it is easily shown that

$$r_{min} = a\left[1 - \sqrt{1 - \frac{n^2}{(n+n')^2}}\right] \tag{19}$$

The most eccentric orbit is that for which $n=1$, $n'=m$, and hence

$$r_{min} = a\left[1 - \sqrt{1 - \frac{1}{(m+1)^2}}\right]$$

Therefore, if a_m is the radius of a circular ring of p electrons each of which has m quanta of azimuthal momentum, it follows from (5) that

$$\frac{r_{min}}{a_m} = \frac{(m+1)^2}{m^2}\left[\frac{Z'_m}{Z'_{m+1}}\right]\left[1-\sqrt{1-\frac{1}{(m+1)^2}}\right] \tag{20}$$

$$\doteqdot \frac{1}{2m^2}\left[\frac{Z'_m}{Z'_m-p}\right]$$

roughly, which shows that, except for special values of Z' and p, there is interference between elliptical orbits and inner circular orbits. For instance, consider the K and L rings. If we assume with Kroo that there are 3 electrons in the K ring, and 9 in the L ring, then

$$Z'_1=Z-0.577$$

for the K ring, and

$$Z'_2=Z-3-3.328$$

$$=Z-6.328$$

for the L ring. Therefore (20) gives

$$\frac{r_{min}}{a_1}=0.536\left[\frac{Z-0.577}{Z-6.328}\right]$$

which is greater than unity only for values of Z less than 13. But there can be twelve electrons in the first two rings only in case Z is equal to or greater than 12. Hence if Kroo's figures are right, elliptic orbits in the second ring will lie entirely outside the first ring only in the case of the element magnesium.

If the variation of mass with velocity is taken into account, it is found that the orbit under an inverse square force of attraction is an ellipse with moving perihelion. The angle through which the perihelion advances per revolution is

$$\pi\frac{e^4Z'^2}{p^2c^2}$$

p being the constant moment of momentum of the electron.

Parenthetically it may be noted that if account is taken of the variation of mass with velocity in the case of a planet revolving around the sun under an inverse square gravitational attraction, the corresponding expression for the advance of the perihelion is only one sixth of that given by Einstein's theory of gravitation.

• Using the method of separation of variables,[1] it is found that the energy of an electron in an orbit characterized by azimuthal quanta n and radial quanta n' is given by

$$\frac{U}{Nh}=\frac{2}{\alpha^2}\left[1+\frac{\alpha^2Z'^2}{(n'+\sqrt{n^2-\alpha^2Z'^2})^2}\right]^{-\frac{1}{2}} \tag{21}$$

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[1] Setting down the expression for the energy

$$U=\frac{m_0c^2}{\sqrt{1-\beta^2}}-\frac{e^2Z'}{r}$$

But

$$\beta^2=\frac{1}{c^2m^2}\left(p_r^2+\frac{1}{r^2}p_\phi^2\right)$$

whence

$$\frac{1}{1-\beta^2}=1+\frac{1}{c^2m_0^2}\left(p_r^2+\frac{1}{r^2}p_\phi^2\right)$$

and

$$r^2\left[p_r^2+m_0^2c^2-\frac{1}{c^2}\left(U+\frac{e^2Z'}{r}\right)^2\right]=-p_\phi^2$$

As the variables are separated, each side may be placed equal to the constant—p^2. It is to be noted in passing that the moment of momentum p_ϕ remains constant during the motion, just as in the case of a particle of invariable mass.

Therefore the quantum conditions become

$$\S p\,d\phi=nh$$

and

$$\S\sqrt{A+2\frac{B}{r}+\frac{C}{r^2}}\,dr=n'h$$

where

$$A\equiv-m_0^2c^2+\frac{U^2}{c^2}$$

$$B\equiv\frac{e^2Z'U}{c^2}$$

$$C\equiv-p^2+\frac{e^4Z'^2}{c^2}$$

As before, the limits of integration of the first integral are taken as 0 and 2π. The and, as before,

$$\frac{\nu}{N}=\frac{U_1}{Nh}-\frac{U_2}{Nh}$$

If (21) is expanded in powers of the small quantity α,

$$(n, n')\equiv-\frac{U}{h}+m_0c^2$$

$$=\frac{NZ'^2}{(n+n')^2}\left\{1+\frac{\alpha^2Z'^2}{(n+n')^2}\left(\frac{1}{4}+\frac{n'}{n}\right)\cdots\right\} \tag{22}$$

where the relativity correction is contained in the second term. As this term involves the ratio of n' to n, it may have different values for the same value of the sum of these quantities.

Consider now an atom containing only one electron, such as the hydrogen atom, or the ionized helium atom. As already noted, the first ring must be circular. The second may consist of a (2,0) circular orbit,[1] or a (1, 1) elliptical orbit. The difference in frequency corresponding to the difference in energy between these two orbits is seen from (22) to be

$$\Delta\nu=(1, 1)-(2, 0)=\frac{N\alpha^2}{2^4}Z^4=\Delta\nu_HZ^4 \tag{23}$$

where $\Delta\nu_H$ is the value of the separation for the second ring in hydrogen.

[1] i. e. n equals 2, n' equals 0.

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second, however, Somerfeld integrates from one minimum of r to the next, which, on account of the advancing perihelion, amounts to integrating over a path a little greater than that corresponding to a single revolution. This procedure, while mathematically convenient, seems somewhat arbitrary from the physical point of view. The integrals are

$$2\pi p=nh$$

$$2\pi i\frac{B}{\sqrt{A}}-2\pi\sqrt{-C}=n'h$$

Eliminating p from these, (21) is obtained.

The third ring has a three fold multiplicity, to which correspond the frequency differences

$$\Delta\nu_1=(2,1)-(3,0)=\frac{N\alpha^2}{3^4}\cdot\frac{1}{2}Z^4=\frac{8}{81}\Delta\nu_H Z^4 \qquad (24)$$

$$\Delta\nu_2=(1,2)-(2,1)=\frac{N\alpha^2}{3^4}\cdot\frac{3}{2}Z^4=\frac{8}{27}\Delta\nu_H Z^4 \qquad (25)$$

and, in general, the multiplicity of any ring equals the number of quanta associated with it. Hence if an electron falls from the *m*th to the *n*th ring, there are possible *mn* lines. If the multiplicity lies in the ring into which the radiating electron falls, a set of doublets (or triplets, etc.) should be obtained having a constant frequency difference throughout the whole series, as in the subordinate series in the visible spectra, and if circular orbits are more probable than elliptical ones, the stronger components of these doublets should be on the long wave length side. If, on the other hand, the multiplicity lies in the ring from which the electron comes (the ring into which it falls being, for instance, the first ring as in the Lyman series of hydrogen) the first line should be a doublet, the second a triplet, etc., the components being more closely crowded together as the frequency increases, as is found in the principal series of the elements.

As the separation $\Delta\nu$ varies with the fourth power of the atomic number, it should be sixteen times as great for ionized helium as for corresponding lines due to hydrogen. This fact, together with the less broadening due to the Döppler effect, suggests that experimental confirmation of the theory should be better in the fine structure of the helium lines than in those of hydrogen. Paschen's investigation of the helium line 4686 gives

$$\Delta\nu_H=0.3645\text{c}\pm 0.0045\text{c}$$

which is in excellent accord with the theoretical value 0.365 *c*.

The *L* ring of the heavier atoms may consist of circular (2, 0) orbits or elliptical (1, 1) orbits. Therefore the Kα line, produced by the passage of an electron from the *L* to the *K* ring, should be a doublet. Moreover, the *L* lines, since they are due to an electron falling from outer rings into the *L* ring, should also be doublets. In applying the simple theory outlined above to these X-ray lines, the effective atomic number Z' must be used instead of the atomic number Z. Moreover, as Z' is a much larger number than Z for hydrogen or helium, more terms of the series (22) must be taken into account. Carrying the expansion further, and putting $n+n'=2$,

$$(2,0)=NZ'^2\left[\frac{1}{2^2}+\frac{1}{4}\,\frac{\alpha^2Z'^2}{2^4}+\frac{1}{8}\,\frac{\alpha^4Z'^4}{2^6}+\frac{5}{64}\,\frac{\alpha^6Z'^6}{2^8}+\frac{35}{128}\,\frac{\alpha^8Z'^8}{2^{10}}\cdots\right]$$

and

$$(1,1)=NZ'^2\left[\frac{1}{2^2}+\frac{5}{4}\,\frac{\alpha^2Z'^2}{2^4}+\frac{21}{8}\,\frac{\alpha^4Z'^4}{2^6}+\frac{429}{64}\,\frac{\alpha^6Z'^6}{2^8}+\frac{3359}{128}\,\frac{\alpha^8Z'^8}{2^{10}}\cdots\right]$$

whence

$$\Delta\nu_L=NZ'^4\frac{\alpha^2}{2^4}\left[1+\frac{5}{2}\,\frac{\alpha^2Z'^2}{2^2}+\frac{53}{8}\,\frac{\alpha^4Z'^4}{2^4}+\frac{831}{32}\,\frac{\alpha^6Z'^6}{2^6}\cdots\right].$$

Sommerfeld finds fair agreement between calculated and observed values of this separation if he takes 3.63 for the nuclear defect, as against 6.33 on Kroo's hypothesis regarding the structure of the *K* and *L* rings. It must be noted, however, that this application of the theory to the fine structure of the X-ray lines cannot be considered as more than very approximate. In the first place, no account has been taken of the change in energy of other electrons in a ring when one electron is added to or removed from the ring. More important, however, is the failure of the theory to take cognizance of the fact that when electrons in the *L* ring are moving in elliptical orbits they penetrate the *K* ring as they approach perihelion. Such penetration will produce perturbations which would be expected to lead to a modification of the simple Balmer formula much greater than that due to the variation of mass with velocity. Nevertheless, the fact that Sommerfeld's theory leads to a constant nuclear defect in the *L* orbit for a range of elements extending from atomic number 40 to 92 seems to warrant two important conclusions: (a) the separation of the X-ray lines into doublets is a relativity-mass effect, and (b) all atoms, at least within this range of atomic numbers, have the same structure in the inner rings.

KOSSEL'S RELATIONS

Before leaving the subject of X-ray spectra, some important combinational relations between the frequencies of different lines should be considered. The Kα line, as already noted, is produced by the passage of an electron from the full *L* to the broken *K* ring, and its frequency is determined solely by the initial and final energies of the atom, according to the relation

$$h\nu_{K\alpha}=U_1-U_2$$

If, now, an electron falls from the M ring into the L ring so as to fill the space left vacant when the $K\alpha$ line was emitted, the $L\alpha$ line is produced, where

$$h\nu_{L\alpha} = U_2 - U_3 ,$$

But, if instead of this double process, an electron had fallen from the M to the K ring in the first instance, such a passage would have given rise to the $K\beta$ line, where

$$h\nu_{K\beta} = U_1 - U_3$$

Therefore we should have

$$\Delta_1 \equiv \nu_{K\alpha} + \nu_{L\alpha} - \nu_{K\beta} = 0 \tag{26}$$

and similarly

$$\Delta_2 \equiv \nu_{L\alpha} + \nu_{M\alpha} - \nu_{L\gamma} = 0 \tag{27}$$

Instead of being zero, however, Δ is a positive quantity greater than the experimental error, which increases with increasing atomic number. Kossel has suggested that the discrepancy is due to a wrong choice of lines:—i. e., that in certain cases where circular orbits have been assumed, the line corresponding to elliptic orbits should have been used. While he is able more nearly to satisfy the theoretical relation in this way, the discrepancy is not entirely removed.

A relation which is better satisfied by the experimental frequencies is one connecting absorption and emission lines. If the inner rings are saturated with electrons, absorption cannot occur until sufficient energy has been supplied to remove an electron to the surface of the atom. This point of view is confirmed by the experimental fact that *none* of the K lines, for instance, are emitted unless the energy of a bombarding cathode particle (or the value of $h\nu$ in the case of exciting radiation) is great enough to pull an electron from the K ring to the confines of the atom. When this happens, however, *all* the K lines appear. Thus it seems impossible to transfer an electron from the K ring of a normal atom to the L ring, indicating that the L ring is already saturated, and cannot take on an additional electron.

Let ν_{K_s} be the absorption frequency corresponding to the removal of an electron from the K ring to the surface of the atom, and ν_{L_s} the corresponding quantity for the L ring. Then, assuming the second postulate of the Bohr theory to apply to absorption as well as to emission, we should have

$$\nu_{L_s} + \nu_{K\alpha} - \nu_{K_s} = 0 \tag{28}$$

a relation which is well confirmed by experiment.

THE STARK EFFECT FOR HYDROGEN

Stark and Lo Surdo have found that some of the emission lines due to gaseous atoms in an electric field of the order of 100,000 volts per cm are split up into a number of components. Confining our attention to hydrogen, the following experimental facts are observed:

(1) Each Balmer line is split up into a number of components.

(2) The number of components increases with the series number of the line.

(3) In the case of transverse observations (at right angles to the lines of force) the components are plane polarized, some *p* (electric vector parallel to the field), and others *s* (electric vector perpendicular to the field).

(4) In the case of longitudinal observation, the *p* components are absent, and the *s* components are unpolarized.

(5) The strong *p* components are in general more displaced from the original line than the strong *s* components.

(6) Displacement and polarization are symmetrical with respect to the original line. This is not always true, however, for elements other than hydrogen.

(7) In hydrogen the distances of the components from the central line are whole multiples of a smallest displacement (measured in frequencies), which is the same for all lines.

(8) The displacement is directly proportional to the field strength.

In the case of a hydrogen atom placed in a strong electric field, the stationary orbits will be distorted from their simple circular or elliptical forms. Hence to apply the quantum conditions it is necessary to find coördinates corresponding to the several degrees of freedom of the revolving electron. This is accomplished by employing two families of oppositely directed confocal paraboloids of revolution having their common focus at the nucleus, and axes parallel to the direction of the applied field E.[1]

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[1] If the X axis is taken parallel to E, the equations of these two families of paraboloids are contained in the single complex equation

$$x+i\rho=\tfrac{1}{2}(\xi+i\eta)^2$$

or, equally well,

$$x-i\rho=\tfrac{1}{2}(\xi-i\eta)^2$$

where

$$\rho^2\equiv y^2+z^2$$

Differentiating, it follows that

$$dx+id\rho=(\xi+i\eta)\,(d\xi+id\eta)$$

and

$$dx - id\rho = (\xi - i\eta)\,(d\xi - id\eta)$$

Multiplying,

$$dx^2 + d\rho^2 = (\xi^2 + \eta^2)\,(d\xi^2 + d\eta^2)$$

If the azimuth of the rotating electron is denoted by ϕ, an element of its path is given by

$$ds^2 = dx^2 + d\rho^2 + \rho^2 d\phi^2$$

$$= (\xi^2 + \eta^2)\,(d\xi^2 + d\eta^2) + \xi^2\eta^2 d\phi^2$$

Therefore its kinetic energy is

$$T = \frac{m}{2}\left[(\xi^2 + \eta^2)\,(\dot{\xi}^2 + \dot{\eta}^2) + \xi^2\eta^2\dot{\phi}^2\right]$$

$$= \frac{1}{2m(\xi^2 + \eta^2)}\left[p_\xi^2 + p_\eta + \left(\frac{1}{\xi^2} + \frac{1}{\eta^2}\right)p_\phi^2\right]$$

and its potential energy

$$V = -\frac{e^2 Z}{r} + eEx$$

$$= \frac{1}{2(\xi^2 + \eta^2)}\left[-4e^2 Z + eE(\xi^4 - \eta^4)\right]$$

Adding, the total energy U is found to be

$$U = \frac{1}{2m(\xi^2 + \eta^2)}\left[p_\xi^2 + p_\eta^2 + \left(\frac{1}{\xi^2} + \frac{1}{\eta^2}\right)p_\phi^2 - 4e^2 mZ + eEm(\xi^4 - \eta^4)\right].$$

As before

$$p_\phi = p = \frac{n_3 h}{2\pi}$$

Therefore the variables are separated if we write

$$\left[p_\xi^2 + \frac{p^2}{\xi^2} - 2e^2 mZ + eEm\xi^4 - 2mU\xi^2\right.$$

$$= -\left[p_\eta^2 + \frac{p^2}{\eta^2} - 2e^2mZ - eEm\eta^4 - 2mU\eta^2\right]$$

Placing each side equal to the constant $2m\gamma$, the quantum conditions become

$$\S\sqrt{2mU + 2m(e^2Z+\gamma)\frac{1}{\xi^2} - \frac{p^2}{\xi^4} - eEm\xi^2}\quad \xi d\xi = n_1h$$

$$\S\sqrt{2mU + 2m(e^2Z-\gamma)\frac{1}{\eta^2} - \frac{p^2}{\eta^4} + eEm\eta^2}\quad \eta d\eta = n_2h$$

Each of these integrals has the form of

$$\S\sqrt{A + 2\frac{B}{r} + \frac{C}{r^2} + Dr}\ dr = 2nh$$

where the last term under the radical is small compared to the preceding one. The integral of this is

$$2\pi i\left\{\frac{B}{\sqrt{A}} + \frac{D}{4A^{3/2}}\left(\frac{3B^2}{A} - C\right)\right\} - 2\pi\sqrt{-C} = 2nh$$

Substituting for A, B, C, and D their values, and eliminating γ from the two equations thus obtained, the expression given in the text for $\frac{U}{h}$ is obtained.

If n_1 and n_2 are the quantum numbers of the motion corresponding to each set of parabolic coördinates, and n_3 that corresponding to the azimuthal motion, the energy of the electron is given by

$$\frac{U}{h} = -\frac{NZ'^2}{(n_1+n_2+n_3)^2} - \frac{3Eh}{8\pi^2meZ}(n_1-n_2)(n_1+n_2+n_3)$$

Hence if m refers to the stationary orbit from which the electron comes, and n to that into which it falls, the displacement (measured in frequencies) of a component from the original line is

$$\Delta\nu = \frac{3Eh}{8\pi^2meZ}\left\{(n_1-n_2)(n_1+n_2+n_3) - (m_1-m_2)(m_1+m_2+m_3)\right\} \quad (29)$$

The amount by which the azimuthal quanta may change is limited by the law of conservation of angular momentum. For a calculation made by Rubinowicz[1] on the basis of the classical electrodynamics shows that the moment of momentum associated with the radiation emitted can never be greater than $h/2\pi$. In obtaining this result, the radiation field is assumed to be that given by the electrodynamic equations for an oscillating Hertzian dipole. The moment of momentum is obtained by multiplying the electromagnetic momentum associated with each element of volume by its lever arm, and summing up. The constant h is then introduced by putting the energy emitted equal to $h\nu$. Now, if the radiation emitted cannot have a moment of momentum greater than $h/2\pi$, the law of conservation of angular momentum requires that the angular momentum of a radiating electron cannot change by more than one unit when the electron passes from one stationary orbit to another. A similar conclusion may be reached from Bohr's comparison of orbital and radiation frequencies. It has been shown that the frequency of the emitted radiation approaches the orbital frequency for circular orbits of large quantum number, provided the angular momentum changes by unity. But it is well recognized that the quantum theory must approximate to the classical theory for low frequencies. Hence it is to be expected that the angular momentum of a radiating electron will always change by unity, and no more. From the experimental point of view, there is evidence that a change in azimuthal quanta from n to $n-1$ is more probable than a change from n to $n+1$, and that a change in radial quanta unaccompanied by a change in azimuthal quanta occurs only in very intense fields. This rule goes by the name of "selection principle."

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[1] Rubinowicz, *Phys. Zeit.*, **19**, 441, 1918.

If the two stationary orbits concerned do not differ in azimuthal quanta, the radiation emitted would be expected to consist of linear electric vibrations parallel to the lines of force. The corresponding components should consist of plane polarized light with the electric vector parallel (p) to the field for transverse observation, and should be absent in the case of longitudinal observation.

On the other hand, if the number of azimuthal quanta associated with the radiating electron changes by a unit, circular vibrations in planes normal to the field would be expected. This should give rise to plane polarized components with the electric vector perpendicular (s) to the field for transverse observation, and unpolarized (because circularly polarized in both senses) components for longitudinal observation.

The $H\alpha$ line of hydrogen is produced by an electron falling from the third to the second ring. Hence

$$\Delta\nu = C(N - M)$$

where

$$N \equiv 2(n_1 - n_2)$$

$$M \equiv 3(m_1 - m_2)$$

Remembering that n_3 and m_3 can never be zero, the following values of $N-M$ are found to be possible,

$$p \text{ components } (n_3-m_3= \quad 0): \pm 2, \pm 3, \pm 4, \pm 8$$

$$s \text{ components } (n_3-m_3=\pm 1): \quad 0, \pm 1, \pm 5, \pm 6$$

Of these, the first three of the p components, and the first two of the s components are found experimentally. The form of (29) shows that the number of components increases as the series number becomes greater.

Not only does the separation vary with the field strength, but excellent quantitative agreement exists between theory and experiment. In certain of Stark's experiments, for instance, the value of E calculated from the observed displacements was 107,000 volts/cm, as against 104,000 volts/cm by direct measurement.

The theory of the Stark effect for ionized helium differs from the above only in the values of the constants involved.

THE ZEEMAN EFFECT

Sommerfeld's attempt to account for the Zeeman effect on the basis of the quantum theory is somewhat artificial, and does not explain any of the abnormal effects with which the electromagnetic theory has trouble. The latter theory leads to an increase δ in the angular velocity of a revolving electron when subjected to a magnetic field H at right angles to its orbit amounting to

$$\delta = \pm \frac{1}{2}\frac{eH}{mc}$$

Take spherical coördinates with polar axis parallel to the applied field. Then the kinetic energy of the electron in the absence of the field is

$$T = \frac{m}{2}\left[\dot{r}^2 + r^2\dot{\theta}^2 + r^2\sin^2\theta\dot{\phi}^2\right]$$

where θ is the polar angle and ϕ the azimuth. In the presence of the field it becomes

$$T + \Delta T = \frac{m}{2}\left[\dot{r}^2 + r^2\dot{\theta}^2 + r^2\sin^2\theta\,(\dot{\phi} + \delta)^2\right]$$

Now Sommerfeld assumes the same quantum conditions in the presence of the field as would be expected to hold in its absence, namely

$$\S\, p_r\, dr = n'h$$

$$\S\, p_\theta d\theta = n_2 h$$

$$\S\, p_\phi d\phi = n_3 h$$

Therefore

$$p_\phi \equiv mr^2 \sin^2\theta\, \dot{\phi}$$

$$= \frac{n_1 h}{2\pi}$$

and, as no appreciable change in potential energy is produced by applying the field,

$$\Delta U = \Delta T$$

$$= \frac{n_1 h}{2\pi}\,\delta\,.$$

Hence the frequency of the emitted radiation differs from what it would be in the absence of the field by the amount

$$\Delta\nu = \frac{n_{1o} - n_{1u}}{2\pi}\,\delta$$

and since the azimuthal quanta cannot change by an amount greater than unity,

$$\Delta\nu = \pm\frac{eH}{4\pi\, mc}, \text{ or } 0 \qquad (30)$$

The constant h does not appear in the final result, which is the same as that obtained accidentally (?) from the classical theory. The polarization of the components may be determined in much the same way as in the case of the Stark effect.

It may be noted that Sommerfeld's theory requires a certain lining up of atomic orbits with the electric field in the Stark effect, and with the magnetic field in the Zeeman effect. Suppose, now that both electric and magnetic fields be applied simultaneously, but so that the lines of force of one field make an angle with those of the other. For special values of this angle it might be possible for atomic orbits to line up with both fields in the manner required by theory, but the necessary conditions certainly could not be satisfied for all angles. It seems that this difficulty merits experimental investigation. Bohr[1] has discussed the case where both fields are in line and of the same order of intensity, as well as the case where the fields make an angle with one another but are of different orders of intensity.

[1] Bohr, "The Quantum Theory of Line-Spectra," Copenhagen, 1918.

The Ritz Formula

Of particular interest is the theory proposed by Sommerfeld to account for the series lines in the visible spectra of elements of higher atomic weight than hydrogen and helium, for these lines are believed to be due to the outermost electron of the atom, and their correct interpretation should yield important information regarding the atom's external structure. The flame and arc spectra are supposed to be produced by a single electron which has been pulled out of the atom and is falling back from one stable orbit to another under the attraction of the nucleus. As the radiating electron is the only one which has been lost, the atom has a single positive charge. The electrons remaining in the atom, however, are at distances from the nucleus comparable to that of the radiating electron, and therefore, the atom cannot be considered as a simple point charge, but its structure must be taken into account in determining the energy associated with each stationary orbit. Suppose that the p inner electrons revolve about the nucleus in a circular ring lying in the same plane as the circular or elliptical orbit of the radiating electron. As a first approximation such a ring may be assumed to have a continuous distribution of electricity along its periphery. Therefore the potential energy of the radiating electron relative to the ring is

$$V = \frac{pe^2}{2\pi r} \cdot \int_0^{2\pi} \frac{d\phi}{\sqrt{1 - 2\frac{a}{r}\cos\phi + \frac{a^2}{r^2}}}$$

where r is the distance of the radiating electron from the nucleus, and a the radius of the ring. If we expand the integrand by the binomial theorem and integrate,

$$V = \frac{pe^2}{r}\left[1 + \frac{1}{4}\frac{a^2}{r^2} + \frac{9}{64}\frac{a^4}{r^4} \ldots\right]$$

Taking account of the fact that the electrons inside the atom may be distributed on more than one ring, and adding the potential energy of the radiating electron relative to the nucleus, the total potential energy of this electron becomes

$$V = -\frac{e^2}{r} + \frac{1}{4}\frac{e^2}{r^3}\sum_i p_i a_i^2 + \frac{9}{64}\frac{e^2}{r^5}\sum_i p_i a_i^4 \ldots$$

Its kinetic energy is

$$T = \frac{1}{2m}\left(p_r^2 + \frac{1}{r^2}p_\phi^2\right)$$

As the force is radial, the moment of momentum p_ϕ is constant, and therefore the quantum condition leads to

$$p_\phi = \frac{nh}{2\pi}.$$

in so far as the azimuthal motion is concerned.

The total energy of the outer electron is

$$U = \frac{1}{2m}\left(p_r^2 + \frac{1}{r^2}p_\phi^2\right) - \frac{e^2}{r} + \frac{1}{4}\frac{e^2}{r^3}\sum_i p_i a_i^2 + \frac{9}{64}\frac{e^2}{r^5}\sum_i p_i a_i^4$$

and, applying the quantum condition to the radial motion, it is found that[1]

$$-\frac{U}{h} = \frac{N}{\left(n+n'+a-\alpha\frac{U}{h}\right)^2} \tag{31}$$

[1] Solving for p_r, the quantum condition for the radial motion is seen to be

$$\S\sqrt{A + 2\frac{B}{r} + \frac{C}{r^2} + \frac{D_1}{r^3} + \frac{D_2}{r^5}}\,dr = n'h$$

where

$$A \equiv 2mU, \quad B \equiv me^2, \quad C \equiv -p_\phi^2 = -\frac{n^2h^2}{4\pi^2}$$

$$D_1 \equiv -\frac{1}{2}me^2\sum_i p_i a_i^2, \quad D_2 \equiv -\frac{9}{32}me^2\sum_i p_i a_i^4$$

Taking account of the fact that the last two terms under the radical are small compared to the preceding ones, integration gives

$$2\pi i\frac{B}{\sqrt{A}} - 2\pi\sqrt{-C}\left\{1 - \frac{1}{2}\frac{B}{C^2}\left(D_1 + \frac{5}{2}D_2\frac{B^2}{C^2} + \frac{15}{8}D_1^2\frac{B}{C^3}\right)\right.$$
$$\left. + \frac{3}{4}\frac{A}{C^3}\left(D_2B + \frac{1}{4}D_1^2\right)\right\} = n'h$$

Substituting for A, B, C, D_1 and D_2, their values as given above, and putting for the radii a_i of the inner rings the values given by (5) in terms of the number of quanta n_i associated with these rings and the effective nuclear charge Z'_i, equation (31) is obtained. In this equation

$$a \equiv \frac{1}{4n^3}\sum_i \frac{n_i^4}{Z'^2_i}p_i + \frac{15}{128n^7}\left\{3\sum_i \frac{n_i^8}{Z'^4_i}p_i - 2\left(\sum_i \frac{n_i^4}{Z'^2_i}p_i\right)^2\right\}$$

$$\alpha N \equiv -\frac{3}{128n^5}\left\{9\sum_i \frac{n_i^8}{Z'^4_i}p_i - 2\left(\sum_i \frac{n_i^4}{Z'^2_i}p_i\right)^2\right\}$$

Sommerfeld seems to have interchanged the signs of the last two terms in the expression for a in the appendix to his book.

Now the spectroscopist finds that the frequencies of lines occurring in the flame or arc spectra are given by differences of two terms of the form of (31), this formula for the frequency being due to Ritz. While $n+n'$ assumes different integral values for different lines of a given element, the number of pairs of values of a and α is comparatively small, and for any one series the values of these constants remain the same for all lines. Therefore the fact that a and α are functions of n but independent of n' indicates that the stationary orbits corresponding to successive lines in a single series are characterized by different values of the radial quantum number n', the number n of azimuthal quanta remaining unchanged.

The expression (31) is usually written by the spectroscopist in the form (m, p) where m stands for $n+n'$, and p specifies the particular constants a and α involved. In the first term of the formula for each series, m is constant, and therefore may be replaced by its numerical value. Thus the various series found are expressed as follows:

Principal Series.........	$\nu=(\frac{3}{2}, s) \quad -(m, p),$	$m=2, 3, 4....,$
First Subordinate Series..	$\nu=(2, p) \quad -(m, d),$	$m=3, 4, 5....,$
Second Subordinate Series	$\nu=(2, p) \quad -(m+\frac{1}{2}, s),$	$m=2, 3, 4....,$
Fundamental (or Bergmann) Series.......	$\nu=(3, d) \quad -(m, b),$	$m=4, 5, 6....$

The fact that the lowest values of m in the variable term of the principal, first subordinate and fundamental series are 2, 3 and 4 respectively leads Sommerfeld to conclude that these numbers represent the number of azimuthal quanta associated with the stable orbits corresponding to the respective series terms. A very puzzling difficulty is presented by the presence of 0.5 in connection with the series number in the constant term of the principal series and the variable term of the second subordinate series. Considerable evidence exists, however, for believing that the s orbits are characterized by one quantum of angular momentum.

The energies corresponding to stable orbits of the s, p, d and b terms are plotted vertically in figure 4. Subscripts designate the total number of quanta associated with each orbit. The lines of the principal series are produced by electrons falling from orbits p_2, p_3, p_4, etc., into s_1. Those in the first subordinate series appear when an electron falls from orbits d_3, d_4, etc., into p_2, and those in the second subordinate series when an electron falls from s_2, s_3, s_4, etc., into p_2. The fundamental series

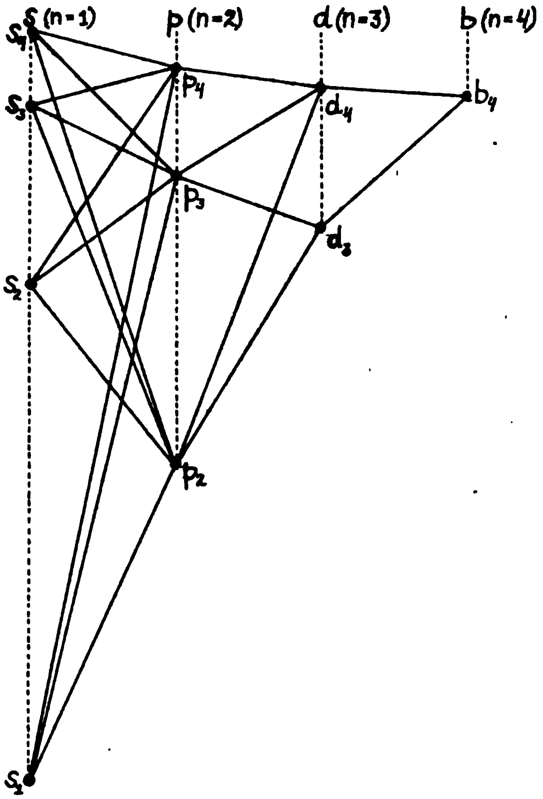

Figure 4. Positions of stability in the atom.

is due to electrons falling from b_4, etc., into d_3. Various combinational lines may be produced when an electron follows the path indicated by one of the other full lines in the figure. It is to be noted, however, that the selection principle is fulfilled in that the azimuthal quanta change by unity in each case.

Stark[1] has pointed out that the relative diffuseness of different lines may be accounted for by the Stark effect. It has been shown in the case of hydrogen, and it is generally true for other elements, that the number of components increases with the series number. Hence the effect of external fields on lines of high series number would be expected to result in a greater diffuseness than in the case of lines of lower series number.

Attempts to devise atomic structures which give values for a and α in good accord with those determined empirically by the spectroscopist have not been very successful. In the variable term of the principal series of the alkalis, for instance, a is positive and α negative (excepting lithium) and both increase in absolute value with increasing atomic number. In the case of sodium, values of these constants agreeing with their empirical values to within 8 or 9 per cent are obtained if the atomic core is assumed to contain two electrons in the first quantum ring, and four each in the second and third, all three rings being circular and lying in the plane of the orbit of the radiating electron.

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[1] Stark, *Ann. d. Phys.*, **58**, 723, 1919.

In the case of un-ionized helium, two systems of series, each containing at least three types of series—principal, first and second subordinate—are known, which seem to be quite independent of one another in that no combinational lines are found involving one term belonging to one system and another belonging to the other. Making use of the theory of perturbations, and applying an hypothesis of Ehrenfest[1] (adiabatic hypothesis) for the quantizing of the orbits, Landé[2] has attempted to account for these lines. He supposes the two electrons to revolve in orbits of different sizes, and not necessarily in the same plane. In order to quantize the orbits in the case of such an atom, the inner electron is supposed to occupy a normal Bohr orbit when the outer electron is at infinity. Then the perturbations in the orbit of the inner electron are computed as the outer electron is slowly brought into the atom. Similarly, the outer electron occupies a normal Bohr orbit when the inner one is attached to the nucleus, and the perturbations of the first are calculated as the second is brought out of the nucleus into its final stationary orbit. While Landé's calculations do not lead to results agreeing very closely with experimental values, they indicate that in the case of the so-called parhelium group of series, the orbits of the two electrons are inclined to one another more or less at right angles, whereas in the case of the helium group the electrons revolve in the same plane. The more stable atomic form is the one with crossed orbits.

Quite recently Sommerfeld[3] has attempted to extend the theory so as to account for doublets and triplets. He concludes that the *s* orbits are single, but the *p* and *d* orbits are multiple—double in the case of doublets and triple in triplets. Examination of the evidence available indicates the presence in the case of multiple orbits of concealed rotations to which a rule similar to the selection principle applies.

The lines in the spark spectra are supposed to be due to a single electron which has been pulled out of a positively ionized atom, and is falling back. In this case the force of attraction on the radiating electron is that due (roughly) to two unit positive charges on the nucleus. Hence its stationary orbits should be determined by an expression of the same form as (31), the Rydberg constant N being replaced by $4\ N$. Recent experimental evidence clearly gives this constant a value for spark spectra four times as great as in the case of arc spectra.

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[1] Ehrenfest, *Phil. Mag.*, **33**, 500, 1917.
[2] Landé, *Phys. Zeit.*, **21**, 114, 1920.
[3] Sommerfeld, *Ann. d. Phys.*, **63**, 221, 1920.

FURTHER ENERGY RELATIONS

The basis of the Bohr theory of atomic structure is the concept of a limited number of stable orbits within the atom, differing from one another in energy by definite steps. In addition to the explanation which this theory provides of certain X-ray and visible emission lines, it accounts for many features of other more or less related phenomena, such as absorption, ionization, etc.

It is convenient to distinguish between rings in the atom, each filled to saturation with electrons, and the free paths outside that are traversed by a single electron which has broken away from one of the inner groups. Neglecting for the moment the slight difference in energy between a circular orbit and an elliptical one having the same quantum number, we may represent schematically the energies of different orbits by horizontal lines drawn at corresponding levels above an arbitrary base line. Thus, in figure 5, the difference in level between the lower lines 1 and 2 is proportional to the excess of energy of an electron in the second Bohr ring in the inner atom, over that of an electron in the first. Suppose the first three rings to be saturated with electrons. Outside these rings exist unoccupied or free orbits of quantum number 1, 2, 3, 4, etc., which an electron that has been pulled out of the inner atom may traverse. If, now, the atom absorbs energy from outside, at least one electron must move to an orbit of greater energy, i.e., to an orbit further from the center of the

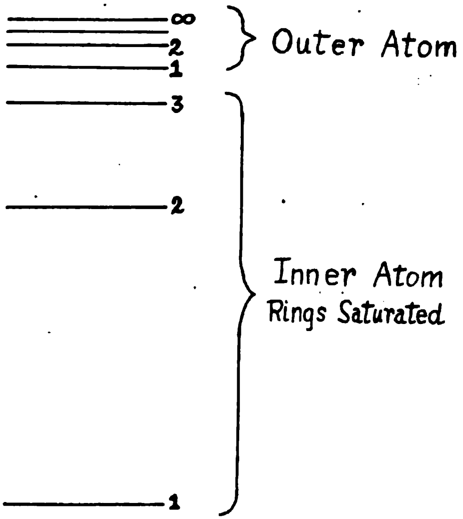

FIGURE 5. Energies of inner and outer rings.

atom. If an electron in the K ring is displaced, however, it cannot take up a position in the already saturated L or M rings, but must either pass on to one of the free orbits outside the inner atom, or leave the atom altogether. Therefore, assuming the second postulate of the Bohr Summerfeld theory to apply to absorption as well as to emission, absorption lines having frequencies equal to those of the K_α and K_β emission lines cannot exist, the lowest frequency in the K absorption spectrum being that corresponding to the removal of an electron from the K ring to the first free orbit outside the inner atom, that is, to the s_1 orbit involved in the visible spectrum. Other lines of higher frequency correspond to the transfer of an electron from the K ring to free orbits further out, and if the atom absorbs enough energy to ionize it, this electron is shot out with a velocity great enough to carry it to infinity. An electron may, however, be ejected with a speed greater than that necessary to take it completely outside the sphere of influence of the atom, and as the kinetic energies of electrons shot out of the atom with such velocities may vary by insensible gradations, continuous absorption would be expected and is actually found.

In the case of the electron responsible for series lines in the visible region, conditions are somewhat different. The free orbits contain no other electrons, and therefore passage is possible from any orbit to any other in either direction. Hence the theory correctly predicts absorption lines of the same frequency as those due to emission.

The single line emission from sodium excited by resonance in Wood's experiments, or by impact of cathode rays by Tate and Foote, has an interesting interpretation on the Bohr Theory. Here the essential condition is that the energy supplied to the electron responsible for the radiation shall be sufficient to remove it from the free orbit in which it is revolving to the next one, and no further. Obviously, the saturated condition of inner orbits negatives the possibility of single line emission in X-ray spectra.

Bohr[1] has pointed out a very interesting confirmation of the selection principle in connection with Strutt's extension of Wood's investigation of the resonance spectrum of sodium. The lines in the principal series of this element are doublets, indicating that the p orbits are double. Now Strutt finds that excitation of sodium vapor with light of the frequency of one of the D lines will produce that D line in the resonance spectrum but not its neighbor. This indicates that the radiating electron cannot pass from one of the p_2 orbits to the other, a transfer that would involve no change in azimuthal quanta. If, however, the exciting radiation has the frequency of the second line in the principal series, the electron has been removed to a p_3 orbit, and may fall back to the s_1 orbit directly, or it may pass to s_2, then to *either* of the p_2 orbits, and finally back to the s_1 orbit. Therefore both D lines appear.

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[1] Bohr, *Zeit. f. Phys.*, **2**, 423, 1920.

To remove an electron from an inner to an outer orbit, the *frequency* ν of the absorbed radiation must be such that $h\nu$ is at least as great as the excess of the atom's energy in the second configuration over that in the first, but the *energy* absorbed may be very much less than this quantity. This fact suggests that energy is stored up, and that the final transfer of the electron from one orbit to the other is due to some sort of trigger action. D. L. Webster,[1] however, has pointed out the following difficulty with this hypothesis. Suppose that almost enough energy to effect the transfer has been stored up from absorbed radiation. Then the impact of a cathode particle of small energy should suffice to complete the process. But it is found that unless an impinging cathode particle is able to supply *all* the excess energy of the final atomic configuration over the initial, the change fails to take place. Such facts seem to indicate that unless the energy of the cathode particle is as great as $h\nu$, none of its energy is available for absorption by the electron under consideration.

THE THREE DIMENSIONAL ATOM

It seems hardly possible that the electronic orbits inside the atom can be all coplanar. Attempts to devise a three dimensional model based on the fundamental postulates of the Bohr-Sommerfeld theory have not as yet, however, been very successful quantitatively. Duane[2] has suggested that there may be two L and two M rings—as is indicated by the recurrence of the numbers 8 and 18 in the periodic table—lying in parallel planes above and below the plane of the K ring. In order to prevent these pairs of rings from coalescing, the electrons must revolve in opposite senses in the two rings of each pair.

Landé[3] has departed more radically from the simple Bohr model in his attempt to construct a cubical atom. In elements of low atomic number he supposes eight electrons situated near the corners of a cube to revolve in small circles about the four principal diagonals of the cube as axes. In the case of elements of high atomic number, the revolution takes place approximately along arcs of four equal circles lying in planes perpendicular to these four principal diagonals and having their common center at the nucleus. This model retains many of the fundamental features of the Bohr theory.

[1] Webster, *Phys. Rev.*, 16, 37, 1920.

[2] Duane, *Phys. Rev.*, 17, 431, 1921.

[3] Landé, *Zeit. f. Phys.*, 2, 380, 1920.

BULLETIN
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NATIONAL RESEARCH COUNCIL

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A LIST OF SEISMOLOGIC STATIONS OF THE WORLD

Compiled under the auspices of the
Section of Seismology of the American Geophysical Union
with the cooperation and assistance of the Research Information Service
National Research Council, United States of America

By Harry O. Wood
Secretary, American Geophysical Union

INTRODUCTION

Because of inquiries and recognition of the need for a revised list of the seismologic stations of the world, the present compilation was undertaken, under the auspices of the Section of Seismology of the American Geophysical Union and with the cooperation of the Research Information Service of the National Research Council of the United States of America.

Under date of March 20, 1920, the following questionnaire, accompanied by the following explanatory letter asking the cooperation of seismologists in the assembly of the necessary data, was sent to every address where a seismograph was known or thought to have been installed or projected (except in a very few cases where former stations were definitely known to have been discontinued). In assembling the list of addresses to which the inquiry was sent the compiler received substantial assistance from Professor H. F. Reid, Professor W. J. Humphreys, and Rev. F. A. Tondorf, S.J., to whom thanks and acknowledgments are tendered.

NATIONAL RESEARCH COUNCIL OF THE UNITED STATES OF AMERICA

RESEARCH INFORMATION SERVICE

DATA FOR LIST OF SEISMOLOGIC STATIONS

Please send information concerning seismologic stations to the
Secretary of the American Geophysical Union, Research Information Service,
National Research Council, Washington, D. C., U. S. A.

STATION
Name --
Location, with Lat. and Long.--
Altitude above sea--
Lithologic foundation---
Date of inauguration--
Postal address--

DIRECTOR
Title---
Name --
Term of office, if limited--
Postal address--

SUPPORTING INSTITUTION (university, observatory, or bureau of government)
Name -- ---
Title of chief officer--
Name --
Term of office, if limited ---
Postal address--

EQUIPMENT—Seismometers, etc., give *types*, *components*, and *constants* of each

TIME-SERVICE—Give *equipment*, *chronographic system employed*, and the *accuracy obtained*.

AUXILIARY APPARATUS—Describe briefly, but give sufficient details.

A new list of seismological stations throughout the world is now an urgent need. No general list has been published since the outbreak of the world war in 1914.

Since then international seismological service has been interrupted, certain domestic services have been disrupted, and sweeping changes in personnel have occurred. Also some new stations have been established, and changes in equipment have been made.

The need for a new list is emphasized by requests for information received recently by the Secretary of the American Geophysical Union, which is the American "National Committee" of the International Geodetic and Geophysical Union established in affiliation with the International Research Council at the international scientific conference held at Brussels in July, 1919.

It therefore seems a fitting task for the Section on Seismology of the American Geophysical Union to initiate inquiries and to undertake the preparation of such a list. In this the Section seeks to cooperate with and to avail itself of the assistance of the Research Information Service established by the National Research Council of the United States to serve as a general bureau of information for scientific and industrial research.

The Research Information Service has many functions to perform, among them the maintenance of catalogs of information affecting progress in research. A list of the seismological stations of the world giving the location and usual constants of the station and its equipment, its personnel, and its institutional foundation is an especially appropriate body of information for this Service to maintain in its files.

Therefore the officers of the American Geophysical Union and its Section of Seismology, and of the Research Information Service, earnestly request that the information indicated on the enclosed questionnaire be sent at your early convenience to the Research Information Service, National Research Council, Washington, D. C., U. S. A.

The value of a list of seismological stations will depend upon its completeness and accuracy. It should be assembled and prepared for publication at an early date.

Assuring you of our great appreciation of your prompt and hearty cooperation in this inquiry,

Yours very truly,
(*Signed*) ROBERT M. YERKES

Robert M. Yerkes, Chairman, Research Information Service
William Bowie, Chairman, American Geophysical Union
Harry Fielding Reid, Chairman, Section of Seismology
Harry O. Wood, Secretary, American Geophysical Union

A second letter was mailed in November, 1920, to those stations which had failed to reply to the first. On the whole the response to this inquiry has been very gratifying indeed, although to date no replies have been received from many of the stations addressed. There are several reasons which may account for this. A considerable number of letters of both mailings have been returned undelivered by the postal services, either because the stations had been discontinued or had never been established, or because of the disorganized status of postal communication in or with certain countries; and perhaps in some instances because of uncertain or inadequate address. It is probable, too, that a small percentage of the letters of both mailings neither reached their destinations nor were returned undelivered. It seems certain, also, that some of the letters were properly delivered but that, for one reason or another, no reply has been received in return. It is known that some early replies went astray. However, except for a neglect to answer on the part of some stations, doubtless due to oversight in most cases, the inquiry has met with cordial support, and many appreciative letters have been received containing suggestions for improvement which are incorporated in a second inquiry which is initiated here with the publication of this list. The publication of a revised list as early as is practicable is intended.

In only two or three cases has the information requested been definitely refused. Each refusal was a consequence of the nationality of the Director of the station. In two cases the refusal was based on the fact that the nation of the writer was not admitted to the International Research Council with which the National

Research Council of the United States is affiliated. In these cases the information desired had to be supplied, so far as possible, from other sources.

Replies have been received covering approximately two hundred and twenty-five stations now in operation and several other projected stations or former stations temporarily discontinued, somewhat less than two hundred and fifty in all. In many cases the data returned are not as complete or specific as is to be desired. It is hoped that the second inquiry, here initiated, will remedy these defects. In the case of these stations, however, the data printed may be considered up to date and authentic, errors of publication excepted.

More than one hundred stations marked in this list with an asterisk (*) are described on the basis of older data, since no replies have been received from these places. For almost all of these the data for the descriptions have been furnished from his own files by Professor Harry Fielding Reid of the Johns Hopkins University, Chairman of the Section of Seismology of the American Geophysical Union. Additional information has been contributed by Professor J. B. Woodworth of Harvard University, and by the Rev. F. A. Tondorf, S.J., of Georgetown University, and in isolated instances by several others.

Beyond mere mention, or simply an address, no information has been obtained regarding stations supposed to be maintained at Dawson, Yukon District, Canada; Frameries, Belgium; Universidad Nacional de Habana, Havana, Cuba; Idria, Jugoslavia; Kinda, Katanga, Belgian Congo; Monteleone-Calabro, Italy; San José, Costa Rica; Collége du Sacré Coeur, Smyrna, Asia Minor; and Szeged, Hungary.

Mexico

The Servicio Seismológico Nacional de Mexico of the Instituto Geológico y del Servicio Seismológico is under the direction of Ing. Leopoldo Salazar Salinas, Director; Ing. Heriberto Camacho, Jefe de la Sección de Seismología; and Manuel Muñez Lumbier, Inspector del Servicio Seismológico.

The operation of seismologic stations at Guadalajara, and at Monterrey will be renewed in a short time. Later, stations will be installed at Morelia, Colina, and Salina Cruz.

Roumania

For the time being the stations in Roumania, and the territory annexed as a result of the war, are out of commission because of the war and the disturbed conditions which have followed it. This service is to be re-established as promptly as circumstances will allow.

At the present time there still exists some uncertainty concerning the stable political boundaries of some of the states which have arisen out of the re-adjustments resulting from the war. At the date of writing Harpoot, Armenia, remains in Turkish territory; and in what was formerly Russian territory in the Caucasus region the stations at Achalkalaki, Batum, Boržom, and Tiflis are now within the boundaries of the republic of Georgia, and those at Baku, Balakhany, and Šemakha are in the republic of Azerbaijan.

In the list the stations have been arranged in the alphabetical order of the places where they are located. A few cross-references have been inserted to facilitate the use of the list.

In preparing the information for printing it was found advisable to depart from the form of the questionnaire sent out, and to state the data in simple English phrases.

Every reasonable effort has been made to minimize error. Nevertheless, under all the circumstances, in dealing with over two hundred responses written, in many cases with the pen, in several different languages with somewhat different notation and symbols and filled out with different degrees of completeness,—together with more than one hundred descriptions based on data several years old in most instances—it is obvious that the list must contain many errors, and that it is sadly incomplete. This practically necessitates the publication of a revised and corrected list at an early date. This revised list should also be improved in accordance with requests and suggestions received. To facilitate this a second, modified form of questionnaire has been prepared. A copy of this is enclosed with each copy of the list.

It is requested that, upon receipt of the list and the accompanying questionnaire, in all cases where it is necessary or desirable to communicate information in addition to or in correction of that published, these revised questionnaires be filled out as completely and precisely as possible and returned at an early time to the designated address.

All into whose hands this list comes are earnestly requested to bring to our attention any errors or omissions of any kind affecting it. Suggestions will be welcomed. These should be submitted by letter at an early date. The whole seismologic fraternity is urged to cooperate in making the revised edition complete and accurate.

The compiler wishes here to express his sincere appreciation of the cordial reception which has been accorded to this effort, and to tender his thanks to all who have so generously assisted in the assembly and preparation of the materials of this list. To Professor Reid, Chairman of the Section of Seismology of the American Geophysical Union, whose contribution to the work has been coordinate with his own, the compiler wishes especially to make grateful acknowledgment.

14 April, 1921.
National Research Council,
Washington, D. C.

AACHEN, GERMANY

Erdbebenstation der Technischen Hochschule Aachen, inaugurated in 1908.

Prof. Dr. P. Wilski, Director.
Markscheide-Institut.

Postal address: Erdbebenstation der Technischen Hochschule, Aachen, Deutschland.

$\varphi = 50°46'49.25''$ N., $\lambda = 6°29'05.7''$ E., h = 179 m.

Lithologic foundation: firm sandstone.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.

Constants:	V	T_0	ϵ	r/T_0^2
N,	215	12.0^s	5.5	0.0010
E,	200	12.6	7.0	0.0013

Wiechert horizontal pendulum, phot. registr., mass 80 kg., three comp. N, E and Z.

Constants:	V	T_0	ϵ	r/T_0^2
N,	105	15.6^s	4.8	0.0002
E,	105	16.4	5.0	0.0002
Z,	69	4.5	3.7	0.05

Time service: time is kept and marked by excellent contact clocks (Riefler, and Strasser und Rohde). Time comparisons made by telegraphic signals from the Hamburg Astronomical Observatory. Time determinations are accurate to ±0.1 sec.

ABISKO, SWEDEN

Abisko Geofysiska Observatorium, seismologic service inaugurated December 1, 1912.
Dr. Bruno Rolf, Director (since May, 1915).
Bror Hedemo, Observer.
Komitén för den Naturvetenskapliga Stationen i Vassijaure.

Postal address: Abisko Geofysiska Observatorium, Abisko, Sweden, or Meteorological Bureau, Stockholm 2, Sweden.

$\varphi=68°20.5'$ N., $\lambda=18°49.3'$ E., $h=385$ m.

Lithologic foundation: concrete block on very hard morainic material, a layer 5 m. thick, on slate or schist (Abisko schist).

Equipment: Wiechert inverted pendulum, mass 130 kg., N comp.
Constants: $V=80$, $T_0=9$ sec., $\epsilon=5$, 10 mm. = 1 minute.
(Installed at Vassijaure in October, 1906, and transferred thence to Abisko in June, 1915.)
Galitzin horizontal pendulum, galvanometric-photographic registr., mass 7.5 kg., two comp. N and E.
Constants: $V=1{,}100$, $A=1.274$ m., $T=11.9$ sec., $\mu^2=$ ca. $+0.06$, 24 mm. = 1 minute.

Time service: contact pendulum clock re-set, or freshly started, once each week by telegraphic signal from Stockholm; time comparisons daily by radiotelegraphic signals from Nauen, and, in winter, from the Eiffel tower; accuracy 1 sec. or better.

*ACCRA, GOLD COAST, AFRICA

Seismologic Station[1], inaugurated in 1912 (?).
Comm. Brit. Ass. Adv. Sci.

$\varphi=5°32'$ N., $\lambda=0°12'$ W.

Equipment: Milne seismograph, E comp.

[1] Our information leaves a doubt as to whether this station has ever been in operation.

*ACHALKALAKI, CAUCASUS, RUSSIA

Seismologic Station, of the second class, of the Russian Service.

$\varphi=41°25'$ N., $\lambda=43°29'09''$ E.

Equipment: Bosch-Omori horizontal pendulum, two comp.

*ADVENT BAY (EBELTOFTHAFEN ?), SPITZBERGEN[1]

Seismological Station, functioned from October 27, 1911, to June 18, 1912.

Dr. G. Rempp, Director.

$\varphi = 78°13'$ N., $\lambda = 15°36'$ E.

Equipment: Mainka horizontal pendulum, N comp.

Constants: $V = \text{ca. } 80$, $T_0 = \text{ca. } 6$ sec.

[1] Cf. Beit. z. Geophysik, XIII, Kl. Mitth. 100-120.

AGRAM, see ZAGREB

*AIGION, GREECE

Seismologic Station.

$\varphi = \text{ca. } 38°14'$ N., $\lambda = \text{ca. } 22°00'$ E.

Equipment: Agamennone seismograph.

AKITA, JAPAN

Meteorological Observatory, seismologic service inaugurated in July, 1914.

K. Funayama, Director.

Supported by the local prefecture.

Postal address: Akita Meteorological Observatory, Akita, Japan.

$\varphi = 39°41'$ N., $\lambda = 140°06'$ E., $h = 60$ m.

Lithologic foundation: soft river-side ground.

Equipment: Imamura horizontal pendulum seismograph, two comp. N and E.

Constants: N, $V = 2$, $T_0 = 8$ sec.; E, $V = 2$, $T_0 = 9$ sec.

Omori horizontal pendulum tremor recorder, two comp. N and E.

Constants: N, $V = 50$, $T_0 = 4$ sec.; E, $V = 50$, $T_0 = 4$ sec.

Time service: time comparisons obtained daily by radio-telegraphic signals from the Tokyo Astronomical Observatory.

ALGER-BOUZARÉAH, ALGERIA

Observatoire d'Alger-Bouzaréah, seismologic service inaugurated in 1911.

Prof. F. Gonnessiat, Director.

Observatoire de l'Université.

Postal address: Station sismique, Observatoire d'Alger-Bouzaréah, Algérie.

$\varphi = 36°48'$ N., $\lambda = 3°02'$ E., $h = 332$ m.

Lithologic foundation: crystalline schists and metamorphic limestones, density 2.8 to 3.0, (Archæan massif).

Equipment: Bosch-Mainka seismograph, mass 400 kg., two comp.

Time service: time is determined by the observatory by meridian transit observations.

ALICANTE, SPAIN

Estación Sismológica de Alicante, inaugurated in July, 1914.

D. Juan Garcia de Lomas, Ingeniero Geógrafo, Director.
Instituto Geográfico y Estadístico.

Postal address: Ingeniero Jefe de la Estación Sismológica de Alicante, España.

$\varphi=38°20'44''$ N., $\lambda=0°28'58.5''$ W., h=35 m.

Lithologic foundation: marls (Lower Cretaceous).

Equipment: and Constants:				Mass	V	T_0	r/T_0^2	m. per hour
Bosch-Omori	seismograph,	N	comp.	25 kg.	21	17.0	0.006	0.9
Bosch-Omori	"	E	"	25 "	21	16.0	0.010	0.9
Vicentini	"	N	"	100 "	68	2.4	0.008	0.6
"	"	E	"	100 "	68	2.4	0.008	0.6
"	"	Z	"	50 "	110	0.8	0.020	0.6

Time service: time is kept and minute time marks are made electromagnetically by a Bosch contact clock compared by radiotelegraphic signals from the Eiffel tower.

ALMERIA, SPAIN

Estación Sismológica de Almería, inaugurated July 1, 1911.

D. Eduardo Torallas Tondo, Ingeniero Geógrafo, Director.
Instituto Geográfico y Estadístico.

Postal address: Estación Sismológica de Almería, España.

$\varphi=36°49'36''$ N., $\lambda=1°13'19.9''$ E., h=65 m.

Lithologic foundation: calcareous rock.

Equipment: and constants:				Mass	V	T_0
Bosch-Omori	seismograph,	N	comp.	25 kg.	15.2	13.3
" "	"	E	"	25 "	14.2	13.8
Vicentini	"	N	"	100 "	83	2.44
"	"	E	"	100 "	85	2.44
"	"	Z	"	50 "	120	0.82

An Agamennone seismoscope.

Time service: time comparisons by radiotelegraphic signals from the Eiffel tower.

AMBULONG, TANAUAN, (BATANGAS) PHILIPPINE ISLANDS

Seismologic Station, inaugurated in July, 1912.

Gregorio Peralta, Observer.
Weather Bureau, Philippine Islands.

Postal address: Seismologic Station, Ambulong, Tanauan, Batangas, P. I., or Manila Observatory, Manila, P. I.

$\varphi = 14^\circ 07'$ N., $\lambda = 121^\circ 04'$ E., $h = 10.5$ m.

Lithologic foundation: water-laid tuff, agglomerate, etc.

Equipment: Vicentini system, Padova type. Agamennone strong-motion seismograph.

Time service: time comparisons by daily telegraphic signals, no chronograph.

ANDALGALA, ARGENTINA

Seismologic Station, inaugurated in August, 1916 (1910).

Dr. Max Schmidt, Observer.

Oficina Meteorológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi = 27^\circ 35' 41''$ S., $\lambda = 66^\circ 19'$ W., $h = 1072.43$ m.

Lithologic foundation: volcanic, (granitic).

Equipment: Milne seismograph, two comp. N and E.

Constants: $T_0 = 17$ sec.; N, 1 mm. displacement $= 0.59''$,
E, 1 mm. " $= 0.51''$.

Time service: light eclipsed once each hour; marks checked four or five times a day with a chronometer compared once or twice a week by telegraphic signals sent to local post-office. "Accuracy not very great." Sun dial, with graphic correction curve, reading approximately to 1 to 5 seconds.

ANN ARBOR, MICHIGAN

Astronomical Observatory, seismologic service inaugurated in 1909.

Prof. William J. Hussey, Director.
University of Michigan.

Postal address: Seismological Station, Astronomical Observatory, University of Michigan, Ann Arbor, Michigan.

$\varphi = 42^\circ 16' 48.7''$ N., $\lambda = 83^\circ 34' 36.4''$ W., $h =$ ca. 282 m.

Lithologic foundation: glacial drift.

Equipment:

Bosch-Omori seismograph, mass 100 kg., two comp.
Wiechert inverted pendulum, mass 100 kg., two comp.
" vertical-motion seismograph.

Time service: time is kept by a sidereal clock; time comparisons are made by meridian circle observations; time is obtained from the clock by a chronograph.

AOMORI, JAPAN

Meteorological Observatory, seismologic service inaugurated in November, 1912.
S. Kimura, Director.

Supported by the local prefecture.

Postal address: Aomori Meteorological Observatory, Aomori, Japan.

$\varphi = 40°50'$ N., $\lambda = 140°45'$ E., $h = 3.3$ m.

Lithologic foundation: sandy ground.

Equipment: Imamura horizontal pendulum seismograph, two comp. N and E.
Constants: N, $V = 2$, $T_0 = 6.4$ sec.; E, $V = 2$, $T_0 = 5.8$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

APIA, SAMOA

Samoa Observatory, seismologic service inaugurated in December, 1902.
Mr. C. J. Westland, Director.

Government of New Zealand.

Postal address: Samoa Observatory, Apia, Samoa.

$\varphi = 13°48'26''$ S., $\lambda = 171°45'$ W., $h = 2$ m.

Lithologic foundation: coral sand and gravel about 50 m. thick, resting on volcanic rock.

Equipment:

Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E, with mech. and phot. registr.

Constants: $V_{\text{mech.}} = 130$, $V_{\text{opt.}} = 1{,}500$, $T_0 = 9$ sec., $\epsilon = 4$ to 5.

Wiechert vertical-motion seismograph, mech. registr.

Constants: $V = 50$, $T_0 = 3$ to 4 sec., $\epsilon = 3$.

Horizontal pendulum, opt. registr.

Constants: $V =$ up to 1,000, $T_0 = 3$ to 4 sec., $\epsilon =$ variable as required.

Time service: time is kept by a Riefler clock provided with mercury-compensated pendulum; time comparisons are made to an accuracy of 0.1 sec. by meridian circle observations; time is marked electromagnetically by a contact pendulum clock; readings of the seismograms are made to an accuracy of 1 sec.

AREQUIPA, PERU

Harvard College Observatory Station, maintains only simple seismoscopes which record the time and horizontal components of (local?) earthquakes, writing on smoked glass. These have been maintained for more than twenty years.

ASAHIGAWA, JAPAN

Meteorological Observatory, seismologic service inaugurated in July, 1919.
Z. Yamada, Director.
Supported by the Hokkaido government.

Postal address: Asahigawa Meteorological Observatory, Asahigawa, Hokkaido, Japan.

$\varphi=43°47'$ N., $\lambda=142°22'$ E., $h=111.3$ m.

Lithologic foundation: rather hard alluvial soil.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V=30$, $T_o=6.8$ sec.; E, $V=30$, $T_o=7.2$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

*ISLAND OF ASCENSION

Seismologic Station, inaugurated in November, 1910.
Eastern, Eastern Extension, and Pacific Telegraph Co.

$\varphi=7°57'$ S., $\lambda=14°21'$ W.

Equipment: Milne seismograph, E comp.

*ASMARA, ERITREA, AFRICA

Stazione Sismica d'Asmara, inaugurated in 1913.
Direzione di Colonizzazione.

Postal address: Stazione Sismica d'Asmara, Asmara, Eritrea, E. Africa.

$\varphi=15°20'10''$ N., $\lambda=38°56'$ E., $h=2,350$ m.

Lithologic foundation: crystalline schist.

Equipment: Agamennone horizontal pendulum, mass 50 kg., two horizontal comp.
Constants: $V=30$, $T_o=8$ to 9 sec.

Time service: a slit in the roof of a room allows the sun to send a narrow band of light on the floor. The time of passage of this band across a meridian line drawn on the floor gives local apparent noon. This is then corrected to mean time and to Greenwich time.

ATHENS, GREECE

Observatoire Nationale d'Athènes, seismologic service inaugurated in June, 1899.
Prof. Dèmétrius Eginitis, Director of the Observatory.
Université Nationale d'Athènes, Gouvernement Hellenique.

Postal address: Station sismologique, Observatoire Nationale d'Athènes, Grèce.

$\varphi=37°58'20''$ N., $\lambda=23°43'00''$ E., $h=95$ m.

Lithologic foundation: limestone.

Equipment:
(Since June, 1899) Agamennone seismograph, mass 200 kg., two comp. NW and NE, length of pendulum = 7.25 m.
(Since Nov., 1910) Mainka bifilar pendulum, mass 136 kg., two comp. N and E.
Constants: $V=60$ to 100, $T_o=5.5.$ to 6.0 sec., $\epsilon=4$ to 5, $r/T_o^2=0.006$ to 0.010.

Time service: time is kept with high precision; time comparisons are made by meridian circle observations.

BAGNÈRES DE BIGORRE, see PIC DU MIDI

BAGUIO (BENGUET), PHILIPPINE ISLANDS

Mirador Observatory, seismologic service inaugurated in 1909.
José de Jesús, Observer.
Weather Bureau, Philippine Islands.

Postal address: Mirador Observatory, Baguio, Benguet, P. I., or Manila Observatory, Manila, P. I.

$\varphi=16°25'$ N., $\lambda=120°36'$ E., $h=1{,}512$ m.

Lithologic foundation: sedimentary rock, (Tertiary).

Equipment: Vicentini system, Manila type. Omori system, Manila type.

Time service: time is kept by a chronometer compared daily by telegrahic signals; no chronograph.

*BAKU, CAUCASUS, RUSSIA

Nobel Seismologic Station, inaugurated in 1903. A station of the first class of the Russian Service.
Nobel Bros.

Postal address: Nobel Seismologic Station, Baku, Caucasus, Russia.

$\varphi=40°23'$ N., $\lambda=49°54'$E.

Lithologic foundation: isolated piers on limestone (Pliocene) in a specially built cellar.

Equipment: Zöllner Repsold seismographs, two comp.

*BALAKHANY, CAUCASUS, RUSSIA

Nobel Seismologic Station, inaugurated in 1903.
Nobel Bros.

Postal address: Nobel Seismologic Station, Balakhany, Caucasus, Russia.

$\varphi=40°27'$ N., $\lambda=49°56'49''$ E.

Lithologic foundation: isolated piers on limestone (Pliocene) in a specially built cellar.

Equipment: Galitzin seismographs, two horizontal comp.

BALBOA HEIGHTS, CANAL ZONE

Seismologic Station, inaugurated October 1, 1914. (Previously at Ancon, inaugurated there in December, 1908.)
R. Z. Kirkpatrick, Chief Hydrographer, in charge.
The Panama Canal.

Postal address: Seismologic Station, Balboa Heights, Canal Zone.

$\varphi=8°57'39''$ N., $\lambda=79°33'29''$ W., h=ca. 36 m.

Lithologic foundation: basalt.

Equipment: Bosch-Omori seismograph, mass 25 kg., two comp. N and E. Constants: $V=10$, $T_0=20$ sec.
Bosch-Omori seismograph, mass 100 kg., two comp. N and E. Constants: $V=35$, $T_0=20$ sec.

Time service: time is kept to an accuracy within one or two sec. by an electric clock corrected hourly; minute time marks made electromagnetically by contact clock.

BALTIMORE, MARYLAND

Johns Hopkins University.

This station was suspended in 1915 on removal of the Johns Hopkins University to its new site.

BARCELONA, see FABRA

*BATUM, CAUCASUS, RUSSIA

Seismologic Station.

$\varphi = 41°40'$ N., $\lambda = 41°38'35''$ E.

Equipment: Bosch-Omori horizontal pendulum, two comp.

BEIRUT, SYRIA

American University Observatory, seismologic service inaugurated about 1902.

Prof. J. A. Brown, Director.
American University of Beirut.

Postal address: Observatory, American University, Beirut, Syria.

$\varphi = 33°54'$ N., $\lambda = 35°28'$ E., h = ca. 30.5 m.

Lithologic foundation: fossiliferous limestone (Upper Cretaceous).

Equipment: Milne seismograph, E comp., $T_0 = 15$ sec.

Time service: of the University Observatory; astronomical clocks compared weekly by transit observations; time comparisons by radiotelegraphic signals from the Eiffel tower will be resumed.

*BEIRUT, SYRIA

Observatoire de Ksara, seismologic service inaugurated in 1911.

Rev. B. Berloty, S. J., Director.
International Seismological Association.

Postal address: Observatoire de Ksara, Saad-Naïl near Beirut, Syria.

$\varphi = 33°49'$ N., $\lambda = 35°53'$ (?) or $37°22'15''$ (?) E, h = 918.5 m.

Lithologic foundation: concrete piers, free from the floor, on solid rock.

Equipment: Mainka horizontal pendulum, two comp.

Time service: time is kept and time marks are made by an excellent clock: time comparisons are made by meridian transit observations.

BELGRADE, SERBIA

Observatoire Séismologique à Tasmïadan-Belgrad, inaugurated August 1, 1909. Operation suspended from October 1, 1915, to July 1, 1920, on account of war.

Prof. Yèlénko Mihaïlovitch, Director.
Institut Géologique de l'Université de Belgrad.

Postal address: Section Séismologique Tasmaïdan-Belgrad, Serbie.

$\varphi = 44°49'17.2''$ N., $\lambda = 20°27'19.7''$ E., h = 128.658 m.

Lithologic foundation: limestone.

Equipment: and constants:			V	T_o	ϵ	r/T_o^2
Wiechert, mass	200 kg.,	NE comp.,	200	8.2 sec.,	6	0.004
" "	200	NW "	200	8.2 "	6	0.004
" "	360	N "	123	5.6 "	1.06	0.022
" "	360	E "	164	6.0 "	1.16	0.016
Belar, "	20	Z "	20	0.6 "	1.07	0.350
Conrad, "	40	N "	80	6.0 "	4	0.005

Agamennone seismoscope.

Time service: time is kept by a Riefler pendulum clock, Graham escapement; and by an electric clock of L. Leroy et Cie.

*BENEVENTO, ITALY

Osservatorio Meteorologico e Geodinamico, seismologic service inaugurated in 1908 (?).
Ufficio Centrale di Meteorologia e di Geodinmica.

Postal address: Osservatorio Meteorologico e Geodinamico, Benevento, Italia.

$\varphi = 41°07'$ N., $\lambda = 14°48'$ E., h = 160 m.

Equipment: Brassart seismometrograph, mass 20 kg., three comp., recording with ink continuously. Brassart seismometrograph which records occasionally with a very open time scale.

Time service: time is controlled by the local telegraph station.

BERGEN, NORWAY

Jordskjalvsstation, inaugurated in 1905.
Prof. Dr. Carl Fred Kolderup, Director.
Bergen Museum.

Postal address: Jordskjalvsstationen, Bergen, Norway.

$\varphi = 60°23'45''$ N., $\lambda = 5°18'18''$ E., h = 20 m.

Lithologic foundation: gneiss.

Equipment: Wiechert inverted pendulum, two comp. N and E. Bosch-Omori seismograph, two comp., N and E.

Time service: time is kept and minute time marks are made electromagnetically by a contact pendulum clock compared twice a week by telegraph with the time of the Astronomical Observatory in Kristiania.

Publication: in Bergen Museum Aarbuk.

BERKELEY, CALIFORNIA

Seismologic Station, inaugurated October 30, 1910. (Earlier service with earlier equipment from 1885.)

Lewis A. Bond, in charge.

Department of Geology, University of California.

Postal address: Seismographic Station, University of California, Berkeley, California.

$\varphi = 37°52'15.9''$ N., $\lambda = 122°15'36.6''$ W., h = 85.4 m.

Lithologic foundation: concrete piers, free from floor, on indurated sandstone (Franciscan).

Equipment: and constants:		V	T_0	ϵ
Bosch-Omori seismograph, mass 100 kg.,	N comp.	80	15	8
“ “ “ 100	E “	80	15	8
Wiechert “ “ 80	Z “	80	6	8
Omori tromometer	N “	60	2	....
“ “	E “	60	2.5	....
Marvin strong-motion seismograph,	N “	5.1	6.5	1.4
“ “ “	E “	5.8	6.5	1.3

Galitzin prisms, for acceleration, two sets N and E.

Time service: time is kept and hour and minute time marks are made electromagnetically by an excellent break-circuit marine chronometer compared at least twice a week by direct electric connection with the Riefler sidereal clock of the Students' Observatory: the probable error of the clock is less than 1 sec.

Measurements, etc., published in semi-annual bulletin, Univ. Calif. Publ.

BESANÇON, FRANCE

Observatoire Nationale de Besançon, seismologic service inaugurated in January, 1910.

Prof. A. Lebeuf, Director of the Observatory.

Université de Besançon.

Postal address: Director, Observatoire de Besançon, Besançon, France.

$\varphi = 47°14'59''$ N., $\lambda = 5°59'15''$ E., h = 311 m.

Lithologic foundation: thin argillaceous strata resting on marls and limestone.

Equipment:
Mainka bifilar pendulum, mass 130 kg., constants not specified,
Kilian-Paulin seismograph,
Seismic alarm, and a seismoscope.

Time service: hour and minute time marks are made electromagnetically by a contact clock which is compared with the time service of the astronomical observatory.

*BIBERACH, GERMANY

Seismologic Station[1], inaugurated in 1905.

Postal address: Seismologic Station, Biberach, Württemberg, Deutschland.

$\varphi = 48°05'03''$ N., $\lambda = 9°47'37''$ E., h = 50 m.

Lithologic foundation: alluvium (Tertiary).

Equipment: Tesdorpf horizontal pendulum, mass 34 kg., two comp.

[1] A sub-station of Hohenheim.

BIDSTON-BIRKENHEAD, see LIVERPOOL

BLACKBURN, ENGLAND

Stonyhurst College Observatory, seismologic service inaugurated July 1, 1909.

Rev. A. L. Cortie, S. J., Director.
Stonyhurst College.

Postal address: Stonyhurst College Observatory, Blackburn, England.

$\varphi = 53°50.7'$ N., $\lambda = 2°28.2'$ W., h = ca. 112.6 m.

Lithologic foundation: stone piers on grit (Millstone) overlying limestones and shales (Carboniferous).

Equipment: Milne seismograph, E comp.

Time service: Light eclipsed once each hour; marks checked once a day with a chronometer; time comparisons made by astronomical observations, and by radiotelegraphic signals from the Eiffel tower. Time marks accurate to one second; readings of seismogram accurate to five seconds.

*BOCHUM, WESTFÄLEN, GERMANY

Erdbebenstation, inaugurated in 1907.

Postal address: Erdbebenstation der Westfälischen Bergewerkschaftkasse, Bochum, Westfälen, Deutschland.

$\varphi = 51°29'36''$ N., $\lambda = 7°13'58''$ E., h = 118 m.

Lithologic foundation: alluvium (8 m.) on calcareous marl on "carboniferous" (70 m.): piers in a special building constructed for the purpose.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. Wiechert inverted pendulum, mass 200 kg., two comp. Wiechert vertical-motion seismograph, mass 1,300 kg. A Wiechert transportable short-period horizontal-and-vertical-motion seismograph for rapid earth vibration.

Time service: time marks are made by a pendulum clock checked daily with an excellent marine chronometer compared weekly with the standard clock of the Geophysikalisches Institut in Göttingen.

BOMBAY, see COLABA

BOM SUCCESSO, MINAS-GERAES, BRAZIL

A Wiechert seismograph, mass 120 kg., is installed here, but as yet there is no time service.

*BORŽOM, CAUCASUS, RUSSIA

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 41°51'$ N., $\lambda = 43°23'$ E.

Equipment: Bosch-Omori horizontal pendulum, two comp.

*BRESLAU-KRIETERN, SILESIA, GERMANY

Seismologic Station, inaugurated in 1907.
Dr. von dem Borne, Director.

Postal address: Seismologic Station, Breslau-Krietern, Schlesien, Deutschland.

$\varphi = 51°04'27''$ N., $\lambda = 16°59'58''$ E., h = 125 m.

Lithologic foundation: diluvium.

Equipment: Wiechert inverted pendulum, mass 1,200 kg., two comp. Wiechert vertical-motion seismograph, mass 1,400 kg.

BRUXELLES, see UCCLE

BUCHAREST, ROUMANIA

Seismologic Station, inaugurated in 1902.
Prof. E. Otetelişanu, Director.

Institutul Meteorologic Central al Romåniei,

Ministerul Agriculturei și Domeniilor.

Postal address: Institutul Meteorologic al Romåniei, Bucureștĭ, Romånia.

$\varphi = 46°31'$ N., $\lambda = 26°06'$ E., h = 82 m.

Lithologic foundation: slate.

Equipment: Bosch horizontal pendulum, mass 10 kg., two comp. Galitzin aperiodic seismometer, photo-gavanometric registration, electromagnetic damping, two comp.

Seismoscopes of Tacchini, Brassart, Agamennone, and Guzzanti types.

Time service: not stated.

BUDAPEST, HUNGARY

Seismological Observatory of the University, inaugurated March 11, 1902; with present equipment January 1, 1906.

Prof. Dr. Rado Kövesligethy, Director.

Geological Institute, Ministry of Culture and Public Instruction.

Postal address: Seismological Observatory of the University, Múzeum Körút 6–8, Budapest, Ungarn.

$\varphi = 47°29'29''$ N., $\lambda = 19°03'55''$ E., h = 110 m.

Lithologic foundation: stone pier on concrete block extending down to water level in sand and alluvium (over Tertiary).

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.

		V	T_0	ϵ	r/T_0^2
Constants:	N,	168	6.3	4.06	0.008
	E,	182	7.2	2.75	0.007

Galitzin horizontal pendulum (second-order station type) mech. registr., two comp. N and E.

Time service: time is kept to an accuracy of 1 sec. by a pendulum clock checked by means of a chronometer with the time service of the Cosmographical Institute of the University.

A Bureau of Seismological Calculations is maintained for theoretical and practical investigations in seismological matters.

Formerly stations at Fiume, Kalocsa, Kolozsvár, Ógyalla, Szeged, Temesvár, and Ungvár were dependent on Budapest as central station.

BUTUAN (AGUSAN), PHILIPPINE ISLANDS

Meteorological Station, seismologic service inaugurated in May, 1915. Generoso Copin, Observer.

Weather Bureau, Philippine Islands.

Postal address: The Meteorological Station, Butuan, Agusan, P. I., or Manila Observatory, Manila, P. I.

$\varphi = 8°56'$ N., $\lambda = 125°32'$ E., h = 2 m.

Lithologic foundation: alluvial.

Equipment: Wiechert inverted pendulum, mass 180 kg.

Time service: time comparisons daily by telegraphic signals; no chronograph.

CADIZ, see SAN FERNANDO

*CAGGIANO, ITALY

R. Osservatorio Meteorico Geodinamico Agrario.

Postal address: Caggiano, Salernitano, Italia.

$\varphi = 40°33'57''$ N., $\lambda = 15°30'$ (or $12°28'59''$?) E., h = 831 (or ca. 820 ?) m.

Lithologic foundation: limestone.

Equipment: Agamennone seismometrograph, mass 200 kg., two comp., registering with ink.

Constants: $V = 12.5$, $T_0 = 6$ sec.

Brassart seismometrograph, three comp., open time scale.

Seismoscopes.

Time service: time is determined to 6 seconds by meridian observations on the sun.

CAIRO, see HELWAN

CALCUTTA, INDIA

Alipore Observatory, seismologic service inaugurated in March, 1915. Dr. Edward Philip Harrison, Meteorologist, Director.

India Meteorological Department.

Postal address: Alipore Observatory, Calcutta, India.

$\varphi = 22°32'$ N., $\lambda = 88°20'$ E., h = 6.4 m.

Lithologic foundation: alluvial.

Equipment: Omori-Ewing horizontal pendulum, mass 50 kg., two comp. N and E.

Constants: N, $V=29$, $T_o=18$ sec.: E, $V=29$, $T_o=30$ sec.

Time service: a clock of known rate and error marks time by electric contact at the beginning and end of the trace; correct to 0.1 minute: minute marks are made electromagnetically by a second clock.

Publication: The data are published along with those of the Bombay, Kodaikanal and Simla Observatories in the India Monthly Weather Review. They are also sent to the British Association Seismological Committee.

CAMBRIDGE, MASSACHUSETTS

Harvard Seismographic Station, inaugurated in April, 1908.
Prof. J. B. Woodworth, in charge.
Department of Geology and Geography, Harvard University.

Postal address: Seismographic Station, Harvard Geological Museum, Oxford Street, Cambridge, Massachusetts.

$\varphi=42°22'36''$ N., $\lambda=71°06'59''$ W., $h=5.367$ m.

Lithologic foundation: glacial sands and clays over shales (paleozoic).

Equipment: Bosch–Omori seismograph, mass 100 kg., two comp. N and E. (Actually N3°E and E3°S).

Constants:	V	T_o	ϵ	
N,	50	25	1.5	15 mm. = 60 sec.
E,	80	23	1.5	

Time service: time is kept and hour and minute time marks are made electromagnetically by a contact clock compared, with an accuracy of 0.3 sec., with the time service of the Harvard Astronomical Observatory. Seismograms are read to the nearest second.

CAPANNOLI VAL d'ERA (PROVINCIA PISA), ITALY

Osservatorio Geodinamico e Stazione Termo-Udometrica "Baldini," seismologic service inaugurated in October, 1909.
Domenico Baldini, Director.

Postal address: Capannoli Val d'Era (Provincia Pisa), Italia.

$\varphi=43°34'40''$ N., $\lambda=10°40'30''$ E., $h=57.31$ m.

Lithologic foundation: blue marl and tufa.

Equipment: Alfani tromograph, mass 50 kg., N comp.

Constants: $V=$ ca. 40, $T_o=18.1$ sec., 100 cm. = ca. 1 hour.

Vicentini seismograph, mass 115 kg., two comp. N and E.

Constants:		V	T_0	cm. per hour
	N,	60	2.2 sec.	ca. 84,
	E,	60	...	ca. 84.

Both components are damped with oil.

Time service: time is kept and hour and minute time marks are made electromagnetically by a contact astronomical clock; time comparisons are made by radiotelegraphic signals from the Eiffel tower. Rate of clock not over ± 1 sec. in 24 hours.

Auxiliary seismologic apparatus:

"Ortosismoscopio," mass 10 kg., $T_0 = 1.2$ sec., with an electric contact seismoscopic clock.

Vicentini seismoscope, continuous registration, mass 10 kg., $T_0 = 1.2$ sec., $V = 20$, 45 cm. = 1 hour.

Vicentini horizontal pendulum seismoscope, continuous registration, mass 10 kg., $V = 15$, $T_0 = 4.4$ sec., 103 cm. = 1 hour.

Agamennone "double effect" seismoscope, with electric contact.

CAPE OF GOOD HOPE, SOUTH AFRICA

Seismologic Station, inaugurated in 1899.

S. S. Hough, H. M. Astronomer at the Cape.
Royal Observatory, Cape of Good Hope.

Postal address: Royal Observatory, Cape of Good Hope, S. A.

$\varphi = 33°56'03.5''$ S., $\lambda = 18°28'41.4''$ E., $h =$ ca. 13 m.

Lithologic foundation: slate (Malmesbury). [Argillaceous schist and quartzite]?

Equipment: Milne-Shaw seismograph, to be installed in place of older Milne instrument.

Time service: not specified, presumably of precise character.

*CAPE VERDE ISLANDS

Seismologic Station, inaugurated in 1911.

$\varphi = 16°30'$ N., $\lambda = 24°00'$ W.,

Equipment: Milne seismograph, E. Comp.

CARDIFF, WALES

Cardiff City Observatory, seismologic service inaugurated December 20, 1909.

Edward Walford, Medical Officer of Health, in charge.
Cardiff Corporation.

Postal address: (of Observatory) Penylan Hill, Cardiff, Glaur.
(of Director) City Hall, Cardiff, Wales.

$\varphi=51°30'$ N., $\lambda=3°10'$ W., h=ca. 61.9 m.

Lithologic foundation: concrete pier, free of floor, on Old Red Sandstone and Silurian formations.

Equipment: Milne seismograph, E comp.

Time service: light eclipsed every hour by an electromagnet controlled by a watch "kept at Greenwich Mean Time."

CARLOFORTE (SARDINIA), ITALY

Regia Stazione Astronomica di Carloforte, seismologic service inaugurated in 1899.
Dr. Giulio Bemporad, Director.
Regia Commissione Geodetica Italiana.

Postal address: Carloforte (Sardegna), Italia.

$\varphi=39°08'09''$ N., $\lambda=8°18'43.5''$ E., h=18 m.

Lithologic foundation: trachyte.

Equipment: Vicentini microseismograph, mass 100 kg., two comp. $V=50$, $T_o=2.3$ sec., 60 cm.=1 hour.

Time service: electromagnetic time marking; time accurate, determined by astronomical observations; service of the International Latitude Observatory.

CARTUJA (GRANADA), SPAIN

Estación Sismológica de Cartuja (Granada), inaugurated January 1, 1903.
Father Emm. Ma. S-Navarro Neumann, S.J., Director.
Colegio-Noviciado de la Compañía de Jesús—Granada.

Postal address: Cartuja (Granada), España. Apartado No. 32.

$\varphi=37°10'43''$ N., $\lambda=3°35'52''$ E., h=770 m.

Lithologic foundation: limestone (Miocene, Tortonian).

Equipment: "Cartuja" bifilar horizontal pendulum, mass 340 kg., two comp. N and E.
Constants: $V=60$, $T_o=10$ sec., $\epsilon=$ca. 4.
"Cartuja" vertical-pendulum horizontal-motion seismograph, mass 280 kg., E comp.

Constants: V=350, $T_0=2$ sec., no damping.

Time service: time is kept and marked by a Bosch contact chronometer (clock); time comparisons are obtained from the Astronomical-Observatory of Cartuja where time is determined by meridian circle observations. Seismograms are read to an accuracy of 1 sec.

Auxiliary apparatus comprises small registering instruments designed by the Director of the Station to record artificial disturbances.

CASAMICCIOLA, GRANDE SENTINELLA, ISCHIA, ITALY

R. Osservatorio Geodinamico Casamicciola, seismologic service inaugurated October 1, 1891.
Dr. Giulio Grablovitz, Director of the Observatory.
R. Ufficio Centrale di Meteorologia e Geodinamica in Roma.

Postal address: R. Osservatorio Geodinamico, Ischia (Napoli), Italia.

$\varphi=40°44'45.4''$ N., $\lambda=13°54'13.9''$ E., h=122.78 m.

Lithologic foundation: argillaceous tuff.

uipment: Seismograph, Cecchi type, two comp. N and E., "occasional" registration on smoked paper; V=1 to 3.
Brassart seismograph, mass 20 kg., continuous registr., 100 mm.=1 hour.
" " "occasional" registr.
Agamennone tromometer, phot. registr.
Horizontal pendulums, oriented hexagonally.
Fixed horizontal pendulums.
Portable horizontal pendulums, mass 3 to 12 kg., V=8 to 15.
Water levels.
Spirit level.
"Vasca sismica."
"The long spiral."

Time service: time is kept by high grade clocks and chronometers; time comparisons are made by astronomical observations.

CATANIA (SICILY), ITALY

R. Osservatorio Geodinamico, seismologic service inaugurated in May, 1891. (An earlier installation was inaugurated in the University in 1880.)
Prof. Gaetano Platania, Director.
Ministero di Agricoltora.

Postal address: R. Osservatorio Geodinamico, Catania (Sicilia), Italia.

$\varphi=37°30'13''$ N., $\lambda=15°05'15''$ E., h=45 m.

Lithologic foundation: lava and sandstone (Quaternary).

Equipment: and constants:		mass	length	1 hour	V	T_0
Vicentini microseismograph,	N,	100 kg.	1.50 m.	60 cm.	60	2.4 sec.
“ “	E,	100	1.50	60	60	2.4
“ “	Z,	45	1.50	60	90	0.82
Cancani seismometrograph	NE,	300	25.30	60	12	10.0
“ “	NW	300	25.30	60	12	10.0

No damping. Several devices no longer in use.

Time service: time is kept by a marine chronometer compared daily with the time service of the Royal Astrophysical Observatory of Catania.

CATANIA, see also MINEO

CERNAUŢI, ROUMANIA

Seismologic Station.

Prof. N. Steliami, Director.
Universitatea din Cernauţi.

Postal address: Institutul de Fizică Cosmică al Universitatei, Cernauţi, România.

$\varphi = 48^\circ 17'$ N., $\lambda = 25^\circ 56'$ E., $h = 225$ m.

Lithologic foundation:

Equipment: Mainka bifilar horizontal pendulum, two comp.

Time service: not stated.

CHACARITA, ARGENTINA

Observatorio Meteorológico, seismologic service inaugurated in January, 1908.

Observer subject to change.
Oficina Meterológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi = 34^\circ 35' 15''$ S., $\lambda = 58^\circ 28' 15''$ W., $h = 25$ m.

Lithologic foundation: alluvial.

Equipment: Bosch-Omori seismograph, two comp. N and E.
Constants: $V = 10$, $T_0 = 20$ sec.

Time service: minute time marks checked by chronometer compared daily by radiotelegraphic signals from Navy Department. "Time very accurate."

CHALCIS, GREECE

This station has been discontinued.

*CHAPELTON, JAMAICA

Seismologic Station, inaugurated in 1910.

J. F. Brennan, Government Meteorologist, proprietor.
Sub-station of the Kingston Station.

Postal address: Mr. J. F. Brennan, Kingston, Jamaica.

Equipment: Ewing duplex seismograph, mass ca. 13.6 kg. V=10.

CHELTENHAM, MARYLAND

Cheltenham Magnetic Observatory, seismologic service inaugurated in November, 1904.

Magnetic observer, in charge: George Hartnell, present incumbent.
United States Coast and Geodetic Survey.

Postal address: Cheltenham Magnetic Observatory, Cheltenham, Maryland: or Division of Terrestrial Magnetism, U. S. C. and G. S., Washington, D. C.

$\varphi = 38°44'$ N., $\lambda = 76°50.5'$ W., h = ca. 72 m.

Lithologic foundation: concrete piers on sand and gravel, 1 to 2 m. thick, over fine sand and clay.

Equipment: Bosch-Omori seismograph, mass 10 kg., two comp. Constants: V=10, $T_0 = 15$ sec.

Time service: two box chronometers; corrections and rates determined by time signals by wireless daily. The time of starting and stopping the record is noted by a chronometer. The seismograph clock, which makes a mark each minute (1 minute=15 mm.) on the smoked paper, is not of a high grade and the rate is somewhat irregular so that the times of the minute marks in the middle of a sheet may at times be in error by a considerable amount, but comparison with the earthquake reports from Washington, D. C., in general show differences less than 10 sec.

CHIAVARI (GENOA), ITALY

Osservatorio meteorologico e sismico, inaugurated July 3, 1909.

Prof. C. Andrea Bianchi, Director.
Seminario Vescovile.

Postal address: Osservatorio meteorologico e sismico, Chiavari (Genova) Italia.

$\varphi = 44°18'55''$ N., $\lambda = 5°39'45''$ E, h=3 m.

Lithologic foundation: alluvial, delta deposits.

Equipment: and constants: Stiattesi horizontal pendulum seismograph, locally modified, mass 250 kg., two comp.

N 35° E, V = 35, T_o = 11 sec., 180 cm. = 1 hour,
S 55° E, V = 46, T_o = 12.8 " 180 " = 1 "

Alfani tromometrograph (horizontal pendulum), mass 120 kg., one comp.

S 55° E, V = 25. T_o = 12 sec., 105 cm. = 1 hour.

Agamennone seismometrograph (horizontal pendulum), mass 50 kg., two comp. N and E;

N, V = 24, T_o = 4 sec., 150 cm. = 1 hour,
E, V = 24, T_o = 4 " 150 " = 1 "

Seismometrograph (ordinary, or vertical, pendulum), mass 600 kg.,
V = 6, T_o = 2.6 sec., 100 cm. = 1 hour.
Certain auxiliary apparatus of secondary importance.

Time service: hour and minute time marks are made electromagnetically by a contact chronometer; time comparisons are made by radiotelegraphic signals from the Effel tower, and also by meridian circle observations.

CHICAGO, ILLINOIS

U. S. Meteorological Observatory, seismologic service inaugurated in March, 1918.

Henry J. Cox, Meteorologist, in charge.
University of Chicago.
U. S. Weather Bureau.

Postal address: Rosenwald Hall, University of Chicago, 58th St. and Ellis Ave., Chicago, Illinois; or U. S. Weather Bureau, Washington, D. C.

$\varphi = 41°47'$ N., $\lambda = 87°37'$ W., h = 180.1 m.

Lithologic foundation: concrete pier, through loose material to bed rock.

Equipment: Milne-Shaw seismograph, two comp. N and E.

Constants:		V	T_o	ϵ
	N,	150	8 sec.	20
	E,	150	12 "	20

Time service: minute time marks are made by means of an electromagnetic shutter operated by a Howard observatory contact clock checked weekly with the time service of the local office of the Hydrographic Office of the U. S. Navy; time-marking considered accurate to 1 to 2 sec.

CHOSHI, JAPAN

Meteorological Observatory, seismologic service inaugurated in September, 1909.

S. Omura, Director.
Supported by Chiba prefecture.

Postal address: Choshi Meteorological Observatory, Choshi, Chiba-ken, Japan.

φ = 35°44′ N., λ = 140°51′ E., h = 18.2 m.

Lithologic foundation: loam (Tertiary).

Equipment: and constants:		V	T_0
Omori horizontal pendulum tromometer,	N comp.,	120	18.0 sec.
" " " "	E "	30	29.3 "
" vertical-motion tromometer,	Z "	20	11.0 "
" horizontal pendulum tremor recorder,	N "	100	4.9 "
" " " " "	E "	100	4.9 "
" strong motion seismograph,	N "	1	8.0 "
" " " "	E "	1	8.0 "
" " " "	Z "	2	8.0 "

Time service: time marks made by a contact chronometer; time comparisons daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*CHRISTCHURCH, NEW ZEALAND

Magnetic Observatory, seismologic service inaugurated in November, 1901.

Postal address: Magnetic Observatory, Christchurch, New Zealand.

φ = 43°31′50″ S., λ = 172°37′18″ E.,

Lithologic foundation: concrete and brick pier on alluvial fan.

Equipment: Milne seismograph, E. comp.

CHUR, SWITZERLAND

Erdbeben-Station, inaugurated in January, 1916.

Prof. Alfred Kreis, Director.
Kantonschule, Chur.

Postal address: Erdbeben-Station, Kantonschule, Chur, Schwyz.

φ = 46°50′55″ N., λ = 9°32′20″ E., h = 630 m.

Lithologic foundation: exposed rock (Bündner schiefer).

Equipment: Bosch horizontal pendulum, mass 100 kg., E comp.
Constants: $V=96$, $T_0=?$, 1.5 cm. = 1 minute.

Time service: time is kept and minute time marks are made by a contact pendulum clock checked twice a week by the telephonic signals of the Swiss telephone system based on radiotelegraphic signals from the Eiffel tower; accuracy ca. 0.2 sec.

CIENFUEGOS, CUBA

The station at one time projected here has never been established.

CIPOLETTI, ARGENTINA

Observatorio Cipoletti, seismologic service inaugurated in July, 1917.

Observer subject to change.
Oficina Meteorológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi=38°56'03''$ S., $\lambda=68°08'$ W., h = 267 m.

Lithologic foundation: alluvial.

Equipment: Milne seismograph, one comp.
Constants: $T_0=18.5$ sec., 1 mm. displacement = 0.41″. 60 mm. = 1 hour.

Time service: light eclipsed once each hour; marks checked four or five times a day with a chronometer compared once or twice a week by telegraphic signals sent to local post-office. "Accuracy not very great" Sun dial, with graphic correction curve, reading approximately to 1 to 5 seconds.

CLAUSTHAL, see KLAUSTHAL

CLERMONT-FERRAND, FRANCE

Station Sismologique de l'Observatoire de Clermont-Ferrand, inaugurated in 1909.

Prof. E. Mathias, Director.

Postal address: Observatoire, Côte de Landois par Clermont-Ferrand (Puy-de-Dôme), France.

$\varphi=45°46'28''$ N., $\lambda=2°58'01''$ E., h = 400 m.

Lithologic foundation: basalt (Quaternary).

Equipment: Bosch-Mainka bifilar pendulum, mass 130 kg., two comp. N and E.

Constants:	L	V	ϵ	r	
N,	20,490	82.5	3.23	1.41	12 mm. = 1 min.
E,	20,130	84.9	3.28	1.52	

Time service: time is kept and minute and ten-minute time marks are made electromagnetically by an excellent contact clock (Hasler and Escher) compared daily by radiotelegraphic signals; seismograms are read to the nearest second. A marine chronometer is also used for time keeping.

CLEVELAND, OHIO

Meteorological and Seismological Observatory, seismologic service inaugurated in 1905.

Rev. Frederick L. Odenbach, S.J., Director.
St. Ignatius College.

Postal address: Meteorological and Seismological Observatory, St. Ignatius College, Cleveland, Ohio.

$\varphi = 41^\circ 29' 08''$ N., $\lambda = 81^\circ 42' 29''$ W., $h = 206$ m.

Lithologic foundation: glacial drift over shale (Cuyahoga).

Equipment: Wiechert inverted pendulum, mass 80 kg., $T_0 = 7$ sec. Hengler horizontal seismograph, mass 80 kg., $V = 400$, $T_0 = 7$ sec. Vertical pendulum seismograph, mass ca. 895 kg., $V = 20$, $T_0 = 1\frac{1}{6}$ sec. (The Wiechert seismograph is stated to be air-damped but the ratio of dumping is not given.)

Time service: time comparisons are obtained by means of radiotelegraphic signals from Paris, and from Arlington.

CLUJ, ROUMANIA

Seismologic Station.

Prof. G. Volsân, Director.
Universitatea din Cluj.

Postal address: Institutul Geografic al Universitatea din Cluj, România

$\varphi = 46^\circ 45'$ N., $\lambda = 23^\circ 39'$ E., $h = 363$ m.

Lithologic foundation:

Equipment: Mainka bifilar horizontal pendulum, mass 210 kg., two comp.

Time service: not stated.

COCOS ISLANDS, see KEELING ISLANDS

COIMBRA, PORTUGAL

Observatorio Meteorológico de Coimbra, seismologic service inaugurated in 1903.

Prof. Dr. Anselmo Ferraz de Carvalho, Director of the Observatory.
Universidad de Coimbra.

Postal address: Observatorio Meteorológico, Coimbra (Cumeada), Portugal.

$\varphi = 40°12'25''$ N., $\lambda = 8°25'30''$ W., h = 140 m.

Lithologic foundation: sandstone (Triassic).

Equipment: Milne seismograph, E comp.
Constants: $T_0 = 22$ to 24 sec., 1 mm. displacement = 0.20 to 0.30″.
Also, since 1915, Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.
Constants: $T_0 = 12$ to 14 sec., $\epsilon = 4$ to 6, $r/T_0^2 = 0.01$ to 0.005.

Time service: time is kept and hour and minute marks are made electromagnetically by a contact clock (Wiechert); time comparisons are made by meridian transit observations; time is kept to an accuracy of ca. 0.1 sec. There are also astronomical clocks.

COLABA (BOMBAY), INDIA

Government Observatory, seismologic service inaugurated in November, 1907.
T. K. Chinmayanandam, Director, of Bombay and Alibag Observatories.
India Meteorological Department.

Postal address: Government Observatory, Colaba, Bombay, India.

$\varphi = 18°53'36''$ N., $\lambda = 72°48'56''$ E., h = 11 m.

Lithologic foundation: trap.

Equipment: Omori-Ewing horizontal pendulum, E comp.
Constants: V = 20 (20 to 40), $T_0 = 32$ sec. (ordinarily).
Colaba seismograph, two comp. N and E.

Time service: minute time marks are made electromagnetically by a standard contact clock.

Data published in India Monthly Weather Review; also sent to the Brit. Ass. Seis. Committee.

COLOMBO, CEYLON

Colombo Observatory, seismologic service inaugurated July 3, 1909. (Instrument previously in operation in Technical Schools, Colombo, Maradana, from 1899.)

A. J. Bamford, Superintendent, Observatory.
Survey Department, Ceylon Government.

Postal address: Colombo Observatory, Bullers' Road, Colombo, Ceylon.

$\varphi = 6°54'18''$ N., $\lambda = 79°52'18''$ E., $h = 7.3$ m.

Lithologic foundation: pier built up from stratum of compact sand, practically a sandstone, through alluvial soil and sand.

Equipment: Milne seismograph, E comp.
Constants: $T_0 = 16$ sec., 1 mm. displacement $= 0.5$ to $0.6''$.

Time service: time is kept by sidereal and mean-time clocks compared by transit observations. The accuracy of the time keeping is greater than the practicable reading of the seismogram (1 mm. = 1 minute).

*CONSTANTINOPLE, ZONE OF THE STRAITS

(Formerly) Observatoire Impériale Météorologique, seismologic service inaugurated in 1895.

COPIAPÓ, CHILE

Estación sismolójica de Copiapó, inaugurated September 14, 1908.
Prof. Luis Sierra Vera, Jefe.
Universidad de Chile.
Servicio Sismolójico de Chile.

Postal address: Jefe Oficina Sismolójica, Copiapó, Atacama, Chile.

$\varphi = 27°21'$ S., $\lambda = 70°21'$ W., $h = 370$ m.

Lithologic foundation: concrete pier, built up from rock, through alluvium.

Equipment: Wiechert inverted pendulum.

Time service: time is kept by a watch chronometer (un reloj cronómetro).

CRACOW, POLAND

Astronomical Observatory of the Jagellon University, seismologic service inaugurated in November, 1903.
Prof. Thaddaeus Banachiewicz, Director.

Postal address: Astronomical Observatory Cracow Poland.

$\varphi = 50°03.9'$ N., $\lambda = 19°57'12''$ E., $h = 205.5$ m.

Lithologic foundation: pillar on cement on alluvial ground.

Equipment: Bosch horizontal pendulum, mass 10 kg., two comp. NW and NE.
Constants: NW comp. out of order temporarily owing to the war.
NE comp., $V = 10$, $T_0 = 0.43$ min.

Time service: minute marks made electromagnetically by a pendulum clock of the observatory; accuracy ca. 2 sec.

CUYABÁ, MATTO GROSSO, BRAZIL

A Bosch-Omori seismograph, mass 20 kg., is to be installed in the Lyceo Salesiano.

CZERNOWITZ, see CERNAUŢI

DAIREN, CHINA (JAPAN)

Meteorological Observatory, seismologic service inaugurated in January, 1918.

S. Migunuchi, Director.

Supported by the Kwanto government.

Postal address: Meteorological Observatory of the Government of Kwanto, Dairen, Kwanto-shu, China.

$\varphi = 38°54'$ N., $\lambda = 121°36'$ E., $h = 96.8$ m.

Lithologic foundation: quartzite.

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.

Constants:

	V	T_0
N,	20	24 sec.
E,	20	25 "
E,	120	25 "

Time service: time comparisons are obtained by astronomical observations.

*DARMSTADT, HESSE, GERMANY

Seismologic Station, inaugurated in 1909 (?).

Prof. Dr. C. Zeissig, Director.

Physikalische Institut der Technischen Hochschule.

Postal address: Physikalische Institut der Technischen Hochschule, Darmstadt, Hessen, Deutschland.

$\varphi = 49°53'$ N., $\lambda = 8°40'$ E., $h = 146$ m.

Lithologic foundation: thin concrete floor directly on the earth surface.

Equipment: Wiechert inverted pendulum, mass 200 kg.

Time service: time is kept and time marks are made by a good clock compared every week with the time service at the Astronomical Observatory at Königstuhl-Heidelberg.

*DAVOS, SWITZERLAND

Seismologic Station.

Prof. Dr. E. Dietz, Director.

Postal address: Seismologic Station, Davos, Schwyz.

$\varphi = 46°48'$ N., $\lambda = 9°49'$ E.,

Equipment: Bosch-Omori horizontal pendulum, two comp.

DE BILT, NETHERLANDS

Royal Netherlands Meteorological Institute, Section V, Terrestrial Magnetism and Seismology, seismologic service inaugurated in 1908.

Dr. C. van Dijk, Adjunct Director.

Postal address: Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

$\varphi = 52°06'$ N., $\lambda = 5°11'$ E., $h = 3$ m.

Lithologic foundation: sand (diluvium).

Equipment: Galitzin seismometers, galvanometric photo. registr., magnetic damping, two comp. N and E.
Constants: $A =$ ca. 138 cm. (before July, 1918, ca. 135 cm.), $T =$ ca. 25 sec., $k =$ ca. 11 (before July, 1918, ca. 17), $\mu^2 = 0$.
Galitzin vertical-motion seismometer, galvanometric photo. registr., to be installed.
Wiechert inverted pendulum, mass 200 kg., two comp. N and E.
Constants: $V_N = 170$, $V_E = 200$, $T_0 = 5$ sec., $\epsilon = 4$.
Bosch horizontal pendulum, mass 25 kg., two comp. N and E.
Constants: $V = 20$, $T_0 = 18$ sec., $\epsilon = 4$.

Time service: time is kept and minute time marks are made electromagnetically by a contact clock (van Huffel); time comparisons made daily, to an accuracy of ca. 0.25 sec., by means of radiotelegraphic signals from the Eiffel tower.

Publication: Further details will be found in Koninklijk Nederlandsch Meteorologisch Institut, No. 108. Also in Seismische Registrierungen in De Bilt.

DEHRA DUN, INDIA

Seismologic Station, inaugurated in July, 1912.

Dr. J. de Graaff Hunter, Mathematical Adviser to the Survey of India, in charge.

Trigonometrical Survey Office.

Postal address: Seismologic Station, Dehra Dun, U. P., India.

$\varphi = 30°19'29''$ N., $\lambda = 78°03'15''$ E., h = ca. 682.8 m.

Lithologic foundation: alluvium.

Equipment: Omori horizontal pendulum, E comp.

Time service: time is kept and minute time marks are made electromagnetically by a contact clock. Time keeping is as accurate as the reading of the seismograms can be.

DENVER, COLORADO

Sacred Heart College Seismological Station, inaugurated in September, 1909.

Rev. Armand W. Forstall, S.J., Director.

Postal address: Seismological Station, Sacred Heart College, Alcott Station, Denver, Colorado.

$\varphi = 39°40'36''$ N., $\lambda = 104°56'54''$ W., h = 1655 m.

Lithologic foundation: conglomerate (Denver Basin).

Equipment: Wiechert inverted pendulum, mass 80 kg.,

Time service: time is kept and hour and minute time marks are made by a contact clock (Wiechert) corrected occasionally by transit observations.

*DERBENT, CAUCASUS, RUSSIA

Seismologic Station.

Observatoire physique de Tiflis.

$\varphi = 42°04'$ N., $\lambda = 48°18'$ E.

Equipment: Bosch-Omori horizontal pendulum, two comp.

DISKO ISLAND, GREENLAND

Seismic Observatory[1], inaugurated in 1907.

Morten T. Porsild, M.Sc., Owner.

Privately maintained.

Postal address: Seismic Observatory, Disko Island, Greenland, via Copenhagen, Denmark.

$\varphi = 69°14'48''$ N., $\lambda = 53°33'24''$ W[2]., h = ca. 15 m.

Lithologic foundation: gneissic rock.

Equipment: Bosch-Omori horizontal pendulum, mass 100 kg., two comp., $T_0 = 20$ to 30 sec.

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[1] This station is not at present in operation.

[2] The longitude given is probably some 28 sec. too far east, but its error is not yet accurately known.

Time service: time is kept by a chronometer and by a Wiechert contact clock compared occasionally by sextant or theodolite observations. Accuracy of time comparisons from 5 to 0.5 sec.

DOMODOSSOLA, ITALY

Osservatorio Meteorologico Rosmini, seismologic service inaugurated in 1905.
Prof. Cav. Don Francesco Pinauda, Director.

Postal address: Osservatorio Meteorologico Rosmini, Domodossola, presso Novara, Piemonte, Italia.

$\varphi = 46°07'$ N., $\lambda = 8°18'$ E., h = 280 m.

Lithologic foundation: alluvium.

Equipment: Omori-Alfani tromometrograph, mass 400 kg., two comp. N 15° E and E 15° S.
Constants: $V = 40$, $T_0 = 10$ sec. (20 sec.)[1], 1 m. = 1 hour.
Several auxiliary seismoscopic devices.

Time service: time is kept by a mean-time, and by a sidereal, chronometer; time comparisons are made by means of meridian transit observations.

[1] Complete period.

DORPAT, or JURJEW, RUSSIA

This station was discontinued in 1915, and its apparatus was sent to Tomsk, Siberia.

*DURLACH i. BR., GERMANY

Seismologic Station, inaugurated in 1905.
Prof. Dr. F. M. Haid, Director.
Naturwissenschaftliche Verein in Karlsruhe.

Postal address: Seismologic Station, Durlach i. Br., Deutschland.

$\varphi = 48°59'46''$ N., $\lambda = 8°28'55''$ E.

Lithologic foundation: sandstone in a tunnel in the Turmberg.

Equipment: Hecker horizontal pendulum, phot. registr., two comp.

Time service: time is supplied by a clock with a Riefler pendulum.

DYCE, ABERDEENSHIRE, SCOTLAND

Seismologic Station, inaugurated in 1914.
Mr. James Edward Crombie, Owner.
Privately maintained.

Postal address: Mr. James E. Crombie, Parkhill House, Dyce, Aberdeenshire, Scotland.

$\varphi = 57°13'$ N., $\lambda = 2°10'$ W., h = ca. 53.3 m.

Lithologic foundation: gravel.

Equipment: Mainka horizontal seismograph, mass 450 kg., two comp. N and E.
Constants: $V = 150$, $T_0 = 10$ sec.
A Milne-Shaw seismograph is in course of installation.

Time service: time is kept and marked by a Bosch observatory clock; time comparisons are made by radiotelegraphic signals from the Eiffel tower.

EBELTOFTHAFEN, see ADVENT BAY (?)

EDINBURGH, SCOTLAND

Royal Observatory.
Prof. R. A. Sampson, Astronomer Royal for Scotland.

Postal address: Royal Observatory, Edinburgh, Scotland.

$\varphi = 55°55'30''$ N., $\lambda = 3°11'03''$ W., h = ca. 132.3 m.

Lithologic foundation: andesitic lava (Devonian).

Equipment: not stated (Milne seismograph?).

Time service: of the Royal Observatory, accurate within a fraction of 1 sec.

EGER (BOHEMIA), CZECHOSLOVAKIA

Erdbebenwarte Eger, inaugurated in November, 1908.
Dr. Georg Irgung, in charge.
Stadtsgemeinde Eger.

Postal address: Erdbebenwarte, Eger, Czechoslovakia.

$\varphi = 50°04'46''$ N., $\lambda = 12°22'34''$ E., h = 430 m.

Lithologic foundation: sand and clay (Tertiary) about 20 m. in thickness, on phyllite.

Equipment: Horizontal pendulum, opt. registr., magnetic damping.
Constants: $V = $ ca. 100, $T_0 = 20$ sec.
Mainka bifilar pendulum, one comp. only N.

Time service: clock with nickel-steel pendulum, accuracy ±2 sec.

*EKATERINBURG, RUSSIA

Seismologic Station, inaugurated October 14, 1913.

$\varphi = 56°49'38.29''$ N., $\lambda = 60°38'18.5''$ E., h = 275 m.

Lithologic foundation: granite.

Equipment: Galitzin seismographs, three comp.

ESKDALEMUIR, LANGHOLM, SCOTLAND

Eskdalemuir Observatory, seismologic service inaugurated in 1908.
Dr. A. Chrichton Mitchell, Superintendent.
Meteorological Office, Department of Civil Aviation, Air Ministry.

Postal address: Eskdalemuir Observatory, Langholm, Scotland.

$\varphi = 55°18'19''$ N., $\lambda = 3°12'19.7''$ W., h = 242 m.

Lithologic foundation: stratified rock (Silurian) traversed by dikes.

Equipment: Galitzin seismometer, photo. galvanometric registr., three comp.

Constants:	T	T_1	μ^2	$2Ak$	l
N,	24.7 sec.	23.1 sec.	+0.032	88,200	118 mm.
E,	24.8 "	23.9 "	−0.015	86,800	118 "
Z,	13.05 "	10.7 "	+0.50	43,500	359 "

Omori seismograph, now out of use.

Time service: time is kept and minute time marks are made by a "Webster" contact clock; a time signal is received from Greenwich each day; seismometric readings are determined to the nearest second.

ETNA, see CATANIA

EWA, see HONOLULU

FABRA, BARCELONA, SPAIN

Estación sismica del Observatorio Fabra, inaugurated in March, 1914.
Prof. Dr. Eduardo Fontseré[1], Director.
Real Academia de Ciencias y Artes, Barcelona.

Postal address: Dr. E. Fontseré, Real Academia de Ciencias y Artes, Barcelona, España.

$\varphi = 41°25'06''$ N., $\lambda = 2°08'$ E., h = 405 m.

Lithologic foundation: slates (Paleozoic).

Equipment:

Mainka bifilar pendulum, mass 141.2 kg., N comp., mass 144.1 kg., E comp.

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[1] Auxiliary personnel: D. Gabriel Campo Cunchillos
D. Manuel Alvarez Castrillón.

Constants:	V	T_0	ϵ	r/T_0^2
N,	78	9.1	3.5	0.015
E,	65	8.6	4.5	0.013

Vicentini microseismograph, mass 56 kg., Z comp.
Constants: $V=125$, $T_0=0.9$ sec.
Vicentini microseismograph, mass 106 kg., two horizontal comp.
Constants not given.

Time service: time is kept "exact to the second" and minute time marks are made electromagnetically by a modified Wiechert contact clock compared daily by radiotelegraphic signals from the Eiffel tower; also by means of meridian circle observations.

*FANNING ISLAND

Seismologic Station.

Postal address: Pacific Cable Co., Fanning Island.

$\varphi=4°00'$ N., $\lambda=159°40'$ W.

Equipment: Milne seismograph, one comp. E.

The island is a coral atoll, 30 miles in circumference, no point of which is more than ca. 305 m. from the sea, nor more than ca. 3 m. above sea level.

FELDBERG, see KÖNIGSTEIN

*FIUME, FIUME FREE STATE

Seismologic Observatory, inaugurated in 1903.

$\varphi=45°19'56''$ N., $\lambda=14°25'40''$ E., $h=20$ m.

Lithologic foundation: folded limestones (Cretaceous).

Equipment: Vicentini seismograph, two horizontal comp.

*FLORENCE, ITALY

Osservatorio Geodinamico del Collegio "alla Querce."

Postal address: Collegio "alla Querce," Firenze, Italia.

$\varphi=43°47'18''$ N., $\lambda=11°16'42''$ E., $h=$ ca. 80 m.

Lithologic foundation: alluvium (Quaternary).

Equipment: Stiattesi horizontal pendulum, mass 250 kg., two comp.
Constants: $V=25$, $T_0=18$ sec.
Nelzi vertical pendulum, mass 50 kg., three comp., recording photographically when started by a seismoscope.
Constants: $V=10$, $T_0=2$ sec.

Time service: the clock is checked by the midday cannon, fired on signal from the R. Osservatorio Meteorico del Museo.

*FLORENCE, ITALY

Osservatorio Ximeniano.
Rev. G. Alfani, Director.
Scuole Pie.

Postal address: Osservatorio Ximeniano, Firenze, Italia.

$\varphi = 43°46'40''$ N., $\lambda = 11°15'23.7''$ E., h = ca. 75 m.

Lithologic foundation: alluvium.

Equipment: Stiattesi horizontal pendulum, mass 500 kg., two comp. N and E.
Constants: $V = 50$, $T_0 = 20$ sec.
Omori tromometer, mass 250 kg., two comp. NW and NE.
Constants: $V = 40$, $T_0 = 18$ sec.
Vicentini microseismograph, mass 450 kg., two comp. N and E.
Constants: $V = 100$, $T_0 = 2.6$ sec.
Vicentini microseismograph, mass 50 kg., Z comp.
Constants: $V = 130$, $T_0 = 1.2$ sec.

QUARTO-CASTELLO, FLORENCE, ITALY

Osservatorio Astrofisico di Quarto, seismologic service inaugurated in 1895.

Prof. Raffaello Stiattesi, Director of the Observatory.

Postal address: Osservatorio di Quarto-Castello, Firenze, Italia.

$\varphi = 43°49'11.39''$ N., $\lambda = 11°13'11''$ E., h = 119.71 m.

Lithologic foundation: compact limestone (Upper Eocene).

Equipment: Vicentini horizontal microseismograph, mass 500 kg.
Constants: length = 9.28 m., $V = 80$, $T_0 = 4.6$ sec., 1.8 m. = 1 hour.
Vicentini vertical microseismograph, mass 50 kg.
Constants: $V = 130$, $T_0 = 1.6$ sec., 1.8 m. = 1 hour.
Stiattesi horizontal pendulum, mass 500 kg., two comp. N and E.
Constants: N, $V = 50$, $T_0 = 21.4$ sec.: E, $V = 50$, $T_0 = 17.4$ sec.
Various subordinate instruments and seismic alarms.

Time service: time comparisons by radiotelegraphic signals received by way of the R. Osservatorio Astronomico di Arcetri; also by meridian passage observations.

*FOGGIA, ITALY

Specola Meteorologica "P. F. Denza."

Postal address: Specola Meteorologica, Foggia, Puglie, Italia.

$\varphi = 41°27'$ N., $\lambda = 15°31'$ E., h = 80 m.

Equipment: Stiattesi horizontal pendulum, mass 500 kg., two comp.
Constants: $V = 50$, $T_0 = 17.5$ sec., 180 cm. = 1 hour.
Agamennone seismoscope.

Time service: time comparisons made with clock at railway station.

FORDHAM, see NEW YORK

*FORT DE FRANCE, MARTINIQUE

Observatoire du Morne-des-Cadets, seismologic service inaugurated about 1902.

Postal address: Observatoire du Morne-des-Cadets, Fort de France, Martinique.

$\varphi = 14°44'09''$ N., $\lambda = 63°29'$ or $61°09'11''$ (?) W., h = 510 m.

Lithologic foundation: tuff over andesite.

Equipment: Bosch-Omori horizontal pendulum, mass 12.5 kg., two comp. Cecchi seismograph.

*FREIBURG i. BR., GERMANY

Seismologic Station, inaugurated in 1905.
Prof. Dr. F. M. Haid, Director.
Naturwissenschaftliche Verein in Karlsruhe.

Postal address: Seismologic Station, Freiburg i. Br., Deutschland.

$\varphi = 47°59'46.4''$ N., $\lambda = 7°51'34.8''$ E., h = 279 m.

Lithologic foundation: gneiss.

Equipment: Hecker horizontal pendulum, phot. registr., two comp.

Mounted in a tunnel in the Schlossberg especially to study bradyseismic movements.

FUKUOKA, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1907.
T. Ikegami, Director.
Supported by the local prefecture.

Postal address: Fukuoka Meteorological Observatory, Fukuoka, Japan.

$\varphi = 33°34.8'$ N., $\lambda = 130°25.4'$ E., h = 4.3 m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.
Constants: N, $V = 120$, $T_0 = 18$ sec.; E, $V = 20$, $T_0 = 26$ sec.

Time service: time marks are made by a contact chronometer; time comparisons are obtained by radio-telephone from the Tokyo Astronomical Observatory.

*GENOA, ITALY

R. Instituto Idrografico.

Postal address: R. Instituto Idrografico, Genova, Italia.

$\varphi = 44°25'$ N., $\lambda = 80°55'$ E., h = ca. 100 m.

Equipment: Vicentini microseismograph, mass 100 kg., two horizontal comp.
Constants: $V = 80$, $T_0 = 2.4$ sec., 60 cm. = 1 hour.
Vicentini microseismograph, mass 50 kg., Z comp.
Constants: $V = 100$, $T_0 = 0.9$ sec., 60 cm. = 1 hour.

Time service: time is determined accurately by a good meridian transit.

GIFU, JAPAN

Meteorological Observatory, seismologic service inaugurated in February, 1910.
Y. Tanaka, Director.
Supported by the local prefecture.

Postal address: Gifu Meteorological Observatory, Gifu, Japan.

$\varphi = 35°24'$ N., $\lambda = 136°46'$ E., h = 12.8 m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V = 50$, $T_0 = 4.0$ sec.; E, $V = 50$, $T_0 = 3.4$ sec.

Time service: time comparisons obtained daily by radio-telegraphic signals from the Tokyo Astronomical Observatory.

*GÖTTINGEN, GERMANY

Seismische Station.
Prof. Dr. E. Wiechert, Director.
Geophysikalisches Institut der Universität.

Postal address: Seismische Station, Geophysikalisches Institut der Universität, Göttingen, Deutschland.

$\varphi=51°33'$ N., $\lambda=9°58'$ E., $h=270$ m.

Lithologic foundation: limestone.

Equipment: Wiechert inverted pendulum, mass 17,000 kg., N comp.
Constants: $V=2{,}100$, $T_0=1.5$ sec., $\epsilon=8.0$, $r=0.3$ mm.
Wiechert inverted pendulum, mass 1,200 kg., two comp. N and E.

Constants:	V	T_0	ϵ	r
N,	152	14	3.9	1.5
E,	172	12.6	3.4	0.9

Wiechert vertical-motion seismograph, mass 1,300 kg., Z comp.
Constants: $V=170$, $T_0=4.8$ sec., $\epsilon=2.8$, $r=0.1$ mm.

Time service: nothing on record, presumably excellent.

*GRAZ, AUSTRIA

Seismologic Station, inaugurated in 1906.
Physikalisches Institut der Universität Graz.

Postal address: Seismologic Station, Physikalisches Institut der Universität, Graz, Österreich.

$\varphi=47°05'$ N., $\lambda=15°27'$ E., $h=$ ca. 375 m.

Lithologic foundation: isolated concrete pillar, 2.5 m. long, in a cellar on shale (Lower Miocene).

Equipment: Wiechert inverted pendulum, mass 1,000 kg.

Time service: time is kept by a Riefler clock; time comparisons every two weeks suffice.

GUAM, GUAM (MARIANNE ISLANDS)

Seismologic Station, inaugurated in 1914.
W. W. Rowley, in charge, under the control of the Governor of Guam.
Weather Bureau, Philippine Islands.

Postal address: Seismologic Station, U. S. Naval Station, Guam, Guam, or Manila Observatory, Manila, P. I.

$\varphi=13°20'$ N., $\lambda=144°45'$ E., $h=3$ m.
13°28′20.3″ 144°44′55.9″ 5 m. (conflicting reports).

Lithologic foundation: concrete, on coral.

Equipment: Wiechert inverted pendulum, mass 180 kg.

Time service: time is marked by a contact clock checked by a chronometer; time comparisons are made by radiotelegraphic signals from Pearl Harbor.

GUATEMALA CITY, GUATEMALA

Georgetown University Co-operative Station, seismologic service inaugurated in March, 1921.
Claudio Urrutia, Director.
Supported by the Government of Guatemala.

Postal address: Señor Claudio Urrutia, Guatemala City, Guatemala, C. A.

Equipment: Wiechert inverted pendulum, mass 80 kg.

Time service: time determinations are made by transit observations.

GUILFORD, ENGLAND

This station is discontinued.

HAKODATE, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1914.
T. Kajinuma, Director.
Supported by the Hokkaido government.

Postal address: Hakodate Meteorological Observatory, Hakodate, Japan.

$\varphi = 41°46'$ N., $\lambda = 140°44'$ E., h = 2.6 m.

Lithologic foundation: new made ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V = 10$, $T_0 = 6.0$ sec.; E, $V = 10$, $T_0 = 7.3$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

HALIFAX, NOVA SCOTIA

Seismologic Station, inaugurated in 1915.
Prof. H. L. Bronson, in charge.
Dalhousie University and The Dominion Observatory.

Postal address: Seismologic Station, Dalhousie University, Halifax, Nova Scotia, or Dominion Observatory, Ottawa, Canada.

$\varphi = 44°38'$ N., $\lambda = 63°36'$ W., h = ca. 46.5 m.

Lithologic foundation: carbonaceous slate (Pre-Cambrian).

Equipment: Mainka bifilar pendulum, mass 139.3 kg., two comp. N and E.
Constants: $T_0 = 10$ sec., $\epsilon = 5$ to 7 according to adjustment.

Time service: time marks are checked each hour on the record by Western Union telegraph signal; correct within 1 to 2 sec.

HAMADA, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1916.
K. Kambara, Director.
Supported by the Shimane prefecture.

Postal address: Hamada Meteorological Observatory, Hamada, Shimane-ken, Japan.

$\varphi = 34°54'$ N., $\lambda = 132°04'$ E., $h = 18$ m.

Lithologic foundation: rock (rocky hill).

Equipment: Omori horizontal pendulum tromometer, E comp.
Constants: $V = 50$, $T_0 = 20$ sec.

Time service: time corrections by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

HAMAMATSU, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1913.
Y. Nagashima, Director.
Supported by the local prefecture.

Postal address: Hamamatsu Meteorological Observatory, Hamamatsu, Japan.

$\varphi = 34°43'$ N., $\lambda = 137°43'$ E., $h = 26.3$ m.

Lithologic foundation: soft soil.

Equipment: Imamura horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V = 15$, $T_0 = 10$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

HAMBURG, GERMANY

Hauptstation für Erdbebenforschung, inaugurated in July, 1898.
Prof. Dr. Richard Schütt, Director.

Dr. Ernst Tams, Privatdozent, Scientific Associate.
Physikalisches Staatslaboratorium der Hamburgischen Universität.

Postal address: (of station) Hamburg 36, Jungiusstrasse 9. (of Director) Prof. Dr. R. Schütt, Hamburg 24, Papenhuderstrasse 8, Deutschland.

$\varphi = 53°33'34''$ N., $\lambda = 9°58'52''$ E., h = 17 m.

Lithologic foundation: large re-inforced concrete block, in a specially constructed building, on marl or boulder clay (geschiebemergel).

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.
Constants: V = ca. 200, T_o = ca. 10 sec.
Wiechert vertical-motion seismograph, mass 1,250 kg., Z comp.
Constants: V = ca. 200, T_o = ca. 5 sec.
Rebeur-Hecker horizontal pendulum, phot. registr., two comp. N and E.
Constants: V = 32, T_o = 17 to 18 sec.

Time service: time is kept and compared and time marks are made by excellent Riefler astronomical clocks and a Lenzkirscher clock; also daily time comparisons are made, by means of a Hipp chronograph, with the time of the Hamburg Astronomical Observatory. Accuracy attained within at least 0.2 sec.

*HARPOOT, ARMENIA

Seismologic Observatory, inaugurated in 1906.
Euphrates College.

Postal address: Seismologic Observatory, Euphrates College, Harpoot, Armenia.

$\varphi = 38°43'$ N., $\lambda = 39°16'$ E., h = 1,310 m.

Lithologic foundation: volcanic rock.

Equipment: Marvin seismograph, mass 900 kg.,
Constants: V = 100, 86 cm. = 1 hour.

HAVANA, CUBA

Estación Seismológica del Observatorio del Colegio de Belén[1], inaugurated February 3, 1907.
Lorenzo Gangoiti, S.J., Director of the Observatory.

Postal address: Observatorio del Colegio de Belén, Habana, Cuba.

$\varphi = 23°06'21''$ N., $\lambda = 82°21'09''$ W., h = 35 m.

Lithologic foundation: limestone.

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[1] The operation of this station is temporarily suspended.

Equipment: Bosch-Omori horizontal pendulum, mass 25 kg., two comp. N and E.

Constants: $V = 10$ to 20, 15 mm. = 1 minute.

Time service: time is kept and hour and minute time marks are made by an excellent pendulum clock (Dent); time comparisons made with the time sent out from Washington.

HAZELMERE, ENGLAND

No station.

HEIDELBERG (BADEN), GERMANY

Erdbebenwarte der Landes-Sternwarte auf d. Koenigstuhl bei Heidelberg (Baden), inaugurated in 1904.

Dr. Max Wolf, Director der Landes-Sternwarte.
Supported by the State of Baden.

Postal address: Landes-Sternwarte, Koenigstuhl, Heidelberg (Baden), Deutschland.

$\varphi = 49°23'55.7''$ N., $\lambda = 8°43'15''$ E., $h = 558$ m.

Lithologic foundation: sandstone (Trias, buntsandstein).

Equipment: (Wiechert) astatic pendulum, mass 2,100 kg., two comp. N and E.

Constants: $V = 140$, $T_0 = 12$ sec., $\epsilon = 2.3$, $r = 0.8$ mm.

Bosch pendulum, two components
Ehlert pendulum, phot. registr. } not now in use.

Time service: time is kept and time marks are made electromagnetically by a clock; time comparisons are obtained from the time service of the observatory. The accuracy of readings is ±0.5 sec.

HELIGOLAND, GERMANY

Seismologic Station of the Biological Station of the State of Heligoland, inaugurated in 1907.

Prof. Dr. Heinke, Director of the Biological Station.
Geophysikalisches Institut der Universität, Göttingen.

Postal address: Seismologic Station, Helgoland, Deutschland.

$\varphi = 54°10'46''$ N., $\lambda = 7°52'58''$ E., $h = 30$ m.

Lithologic foundation: (instruments to be re-mounted on) sandstone.

Equipment: Wiechert inverted pendulum, temporarily out of use.

Time service: time comparisons (will be made) by radiotelegraphic signals.

HELWAN, EGYPT

Helwan Observatory, seismologic service inaugurated January 1, 1904.
K. Knox-Shaw, Director of the Observatory.
Physical Department, Public Works Ministry, Egypt.

Postal address: Observatory, Helwan, Egypt.

$\varphi = 29°51'34''$ N., $\lambda = 31°20'30''$ E., $h = 116$ m.

Lithologic foundation: limestone.

Equipment[1]: Milne seismograph, two comp. N and E, 25 cm. = 1 hour.

Time service: time is kept and the light is eclipsed every hour by the mean time clock of the Observatory. (The Observatory conducts the time service of Egypt.) The time marks are accurate to 0.5 sec.

[1] A Milne-Shaw seismograph is to be installed.

HIKONE, JAPAN

Meteorological Observatory, seismologic service inaugurated in March, 1909.
S. Maeda, Director.
Supported by the local prefecture.

Postal address: Hikone Meteorological Observatory, Hikone, Japan.

$\varphi = 35°16'$ N., $\lambda = 136°15'$ E., $h = 87.3$ m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V = 50$, $T_0 = 2.0$ sec.; E, $V = 50$, $T_0 = 2.8$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

HIROSHIMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in May, 1915.
K. Nakamura, Director.
Supported by the local prefecture.

Postal address: Hiroshima Meteorological Observatory, Hiroshima, Japan.

$\varphi = 34°23'$ N., $\lambda = 132°27'$ E., $h = 1.7$ m.

Lithologic foundation: sandy soil.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V=20$, $T_0=7.5$ sec.; E, not stated (the same?).

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

HOF (BAVARIA), GERMANY

Erdbeben-Station, inaugurated October 1, 1903.
Fr. Adami, Oberstudienrat, in charge.
Nordoberfränkischer Verein für Natur-, Geschicts-, und Landeskunde.

Postal address: Erdbeben-Station, Hof (Bayern), Deutschland.

$\varphi=50°19.6'$ N., $\lambda=11°55.4'$ E., $h=510$ m.

Lithologic foundation: diabase.

Equipment: (Wiechert) horizontal and vertical seismographs.
Constants: $V=80$ (can be changed to 240).
Time service: not stated.

*HOHENHEIM, GERMANY

Kgl. Württembergische Meteorologische Station, seismologic service inaugurated in 1893, re-installed in 1905.

Prof. Dr. K. Mack, Director.
Kgl. Landwirtschaftliche Hochschule.

Postal address: Kgl. Württembergische Meteorologische Station, Hohenheim, bei Stuttgart, Württemberg, Deutschland.

$\varphi=48°43'$ N., $\lambda=9°13'$ E., $h=392$ m.

Lithologic foundation: alluvium on sandstone.

Equipment: Bosch-Omori horizontal pendulum, two comp.
Schmidt trifilar gravimeter.

HOKOTO (PESCADORES), FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1897.
Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi=23°32'$ N., $\lambda=119°33'$ E., $h=11$ m.

Lithologic foundation: basaltic.

Equipment: Gray-Milne seismograph; also since June, 1902, Omori horizontal pendulum tromometer, mass 6 kg., E comp.

Constants: $V=6$, $T_0=12$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

HONOLULU (EWA), T. H.

Honolulu Magnetic Observatory, seismologic service inaugurated in April, 1903.

Magnetic observer, in charge, subject to change; H. E. McComb, present incumbent.

U. S. Coast and Geodetic Survey.

Postal address: (of observatory) Ewa, Oahu, T. H.; also, U. S. Coast and Geodetic Survey, Washington, D. C.

$\varphi=21°19'12''$ N., $\lambda=188°03'48''$ W., $h=15$ m.

Lithologic foundation: coral, on basalt.

Equipment: Milne seismograph, mass 0.255 kg., E comp. (Loaned by the Earthquake Investigation Committee of the British Association for the Advancement of Science).

Constants: $V=6$, $T_0=18$ sec., 1 mm. displacement $=0.4''$.

This instrument is soon to be replaced by a Milne-Shaw seismograph, two comp.

Time service: Time is determined by solar observations 3 or 4 times a month and carried by two box chronometers. The seismograph clock is compared daily with one of the chronometers. The minute hand of the clock marks the seismogram every hour by cutting off the light near the edge of the paper. The space between hour marks is about 60 mm. The daily rate of the clock is satisfactory but there is some irregularity in the motion of the paper.

HONOLULU, T. H.

Seismologic Station, inaugurated in 1921.

Dr. Arnold Romberg, Professor of Physics, in charge.

University of Hawaii.

Postal address: Dr. Arnold Romberg, University of Hawaii, Honolulu, T. H.

$\varphi=21°\ 18'$ N., $\lambda=157°\ 49.3'$ W., $h=$ ca. 19.8 m.

Lithologic foundation: alluvium, on basalt, near middle of valley about 1.6 km. wide.

Equipment: Romberg horizontal pendulum, mass ca. 31.75 kg., two comp. N and E, phot. registr., with viscous coupling to eliminate effects of slow tilting.

Constants: $V=50$, $T_o=60$ sec., $\epsilon=5:1$ (oil damping); no pivots.

Time service: time is kept and marked by a clock with a wooden pendulum; time comparisons are made by radiotelegraphic signals sent out daily from Pearl Harbor, error ca. one second.

INNSBRUCK, AUSTRIA

Institut für Kosmische Physik, seismologic service inaugurated December 15, 1913.

Prof. Dr. Albert Defaut, Director.
Universität Innsbruck, Austria.

Postal address: Institut für Kosmische Physik, Innsbruch, Schöpfste 41, Österreich.

$\varphi=47°16'$ N., $\lambda=11°24'$ E., $h=580$ m.

Lithologic foundation: river alluvium.

Equipment: Mainka horizontal pendulum, mass 135 kg., two comp. NE and NW.
Constants: $V=$ ca. 100, $T_o=10$ to 12 sec., $\epsilon=4$ to 5, $r/T_o^2=0.007$ to 0.01.

Time service: time is kept and marked with high accuracy, error less than one second.

*IRKUTSK, SIBERIA, RUSSIA

Meteorological and Magnetic Observatory, seismologic service inaugurated in December, 1901.

Postal address: Meteorological and Magnetic Observatory, Irkutsk, Siberia, Russia.

$\varphi=52°16'17.5''$ N., $\lambda=104°18'33''$ E., $h=470$ m.

Lithologic foundation: instruments housed in a specially constructed building on hard clay (Jurassic).

Equipment: Milne seismograph, E comp. Zöllner-Repsold seismograph, mass 50 kg., two horizontal comp., 18 cm. = 1 hour. Bosch-Omori horizontal pendulum, two comp.

Time service: the Observatory is also an astronomical observatory.

IRKUTSK, see also KABANSK

IROSIN (SORSOGON), PHILIPPINE ISLANDS

Seismologic Station, inaugurated in May, 1919.

Eliseo Villalón, Observer.
Weather Bureau, Philippine Islands.

Postal address: The Observer at Irosin, Sorsogon, P. I., or Manila Observatory, Manila, P. I.

$\varphi = 12°43'$ N., $\lambda = 124°02'$ E., h = 29 m.

Lithologic foundation: basalt and andesite.

Equipment: Vicentini system, Manila type.

Time service: time comparisons daily by telegraphic signals; no chronograph.

ISHIGAKIJIMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1915.
T. Iwasaki, Director.

Supported by the Central Meteorological Observatory.

Postal address: Ishigakijima Meteorological Observatory, Okinawa-ken, Japan.

$\varphi = 24°20'$ N., $\lambda = 124°10'$ E., h = 5.5 m.

Lithologic foundation: coral reef.

Equipment: C. M. O. horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V = 20$, $T_0 = 7$ sec.; E, $V = 20$, $T_0 = 6$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

ITHACA, NEW YORK

Seismograph Station.

Department of Geology, Cornell University.

Postal address: Seismograph Station, Department of Geology, Cornell University, Ithaca, New York.

$\varphi = 42°26'58''$ N., $\lambda = 76°29'09''$ W., h = 242.6 m.

Lithologic foundation: not stated.

Equipment: Bosch-Omori horizontal pendulum, mass 25 kg., two comp. N and E.

Constants:

	V	T_0	ϵ
N,	13	24	4
E,	12	21	4

Time service: time is kept and marked by a contact clock compared with a clock kept in the Astronomical Department, College of Civil Engineering. Recent service not accurate.

JENA, GERMANY

"Zentralstelle für Erdbebenforschung. Die Zentralstelle für Erdbebenforschung wurde im Jahre 1898 in Strassburg begründet. 1919 wurde sie nach Jena verlegt und übernahm die seismische Station Jena."

Prof. Dr. Oskar Hecker, Director.
Reichsministerium des Innern.

Postal address: Zentralstelle für Erdbebenforschung, Schillergäszchen 2, Jena, Deutschland.

$\varphi = 50^\circ 55' 36''$ N., $\lambda = 11^\circ 35' 03''$ E., $h = 154.2$ m.

Lithologic foundation: limestone.

Equipment: Wiechert inverted pendulum, mass 1,200 kg., $V = 200$. Straübel vertical seismograph, $V = 2{,}000$.
"Die Station wird wahrscheinlich in Kürze erheblich vergrössert werden."

Time service: daily radiotelegraphic time signals received; clock correction known with an accuracy of ca. 0.2 sec.

JINSEN, KOREA, JAPAN

Meteorological Observatory, seismologic service inaugurated January 1, 1915.

T. Hirata (or Dr. I. Goto), Director.
Supported by the Choshen (Korea) Government General.

Postal address: Meteorological Observatory of the Government General of Choshen, Jinsen, Choshen (Chemulpo), Korea.

$\varphi = 37^\circ 29'$ N., $\lambda = 126^\circ 37'$ E., $h = 69$ m.

Lithologic foundation: granite.

Equipment: Omori horizontal pendulum tromometer, mass 50 kg., two comp. N and E.

Constants:

	V	T_0
N,	20	30 sec.
N,	150	12 "
E,	150	28 "

Time service: minute time marks made by a contact chronometer; time comparisons obtained by transit observations twice a week.

JOHANNESBURG, SOUTH AFRICA

Union Observatory, seismologic service inaugurated in July, 1910.

H. E. Wood, Chief Assistant, in charge.
Union of South Africa.

Postal address: Union Observatory, Johannesburg, South Africa.

$\varphi = 26°11'$ S., $\lambda = 28°04'$ E., h = ca. 1806 m.

Lithologic foundation: quartzite.

Equipment: Wiechert inverted pendulum, mass 200 kg., two comp. N and E.
Wiechert vertical-motion seismograph, mass 160 kg.

Time service: minute marks are made by an auxiliary contact clock, compared with the time service of the Observatory. Records can be read to about 0.05 minute.

*JUGENHEIM, HESSE, GERMANY

Seismologic Station, inaugurated in 1908.
Prof. Dr. C. Zeissig, Director.
Grossh. Technische Hochschule, Darmstadt.

Postal address: Grossh. Technische Hochschule, Darmstadt, Hessen, Deutschland.

$\varphi = 49°45'30''$ N., $\lambda = 8°39'$ E., h = 125 m.

Lithologic foundation: solid concrete base on gravel.

Equipment: Wiechert inverted seismograph, mass 1,200 kg., two comp. recording with ink on white paper.

Time service: time is kept by a standard clock with a Riefler pendulum; time comparisons are made frequently by telephonic signals from the Astronomical Observatory at Kōnigstuhl-Heidelberg; time is marked by a clock checked frequently with the standard clock.

JURJEW, see DORPAT

*KABANSK, near IRKUTSK, SIBERIA, RUSSIA

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 53°03'$ N., $\lambda = 106°37'$ E.,

Equipment: Galitzin horizontal pendulum, mech. registr., two comp.
Galitzin vertical-motion seismograph, mech. registr.

KAGOSHIMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in July, 1915.
N. Maeda, Director.
Supported by the local prefecture.

Postal address: Kagoshima Meteorological Observatory, Kagoshima, Japan.

$\varphi = 31°34'$ N., $\lambda = 130°33'$ E., h = 4.2 m.

Lithologic foundation: soft ground, volcanic ash.

Equipment: and constants:		V	T_0
Omori horizontal pendulum tremor recorder,	N comp.	50	3.6 sec.
" " " " "	E "	50	3.8 "
Imamura seismograph,	N "	2	8.0 "
" "	E "	2	
" "	Z "	2	3.0 "

Time service: Time comparisons are obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*KALAMATA, GREECE

Seismologic Observatory.
Prof. D. Eginitis, Director.
Observatoire Nationale d'Athénes.

$\varphi = 37°02'$ N., $\lambda = 22°15'$ E., h = 32 m.

Equipment: Agamennone seismograph, registering with ink.

KALOCSA, HUNGARY

Haynald Observatorium, seismologic service inaugurated in 1909.
Dr. Theodore Angehrn, S.J., Director.

Postal address: Haynald Observatorium, Kalocsa, Hungary.

$\varphi = 46°31'42''$ N., $\lambda = 18°58'55''$ E., h = 110 m.

Lithologic foundation: heaped up earth.

Equipment: Wiechert inverted pendulum, mass 200 kg., at present out of use.

Time service: time is kept and minute time marks are made electromagnetically by a contact clock (Cook) with a mercury-compensation pendulum; time comparisons are made by astronomical observations.

KANAYAMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in September, 1917.
R. Sano, Director.
Privately supported.

Postal address: Kanayama Meteorological Observatory, Kanayama, Miyagi-ken, Japan.

$\varphi = 37°53'$ N., $\lambda = 140°46'$ E., h = 22.5 m.

Lithologic foundation: rocky ground.

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.
Constants: N, $V=50$, $T_0=16$ sec.; E, $V=20$, $T_0=10$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical observatory.

KANAZAWA, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1908.
Y. Kaneda, Director.
Supported by the Ishikawa prefecture.

Postal address: Kanazawa Meteorological Observatory, Kanazawa, Ishikawa-ken, Japan.

$\varphi=36°32'$ N., $\lambda=136°39'$ E., $h=27$ m.

Lithologic foundation: hard gravel.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V=30$, $T_0=3.4$ sec.

Time service: time corrections by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

KARENKO, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1911.
Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi=23°59'$ N., $\lambda=121°37'$ E., $h=19.2$ m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; Imamura small horizontal pendulum seismometer, two components; also, since January, 1914, Omori horizontal pendulum tromometer, mass 13.5 kg., two comp. N and E.
Constants: $V=35$, $T_0=4$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

*KAŠGAR (CHINESE TURKESTAN), RUSSIA

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 39°27'$ N., $\lambda = 70°01.5'$ E.

Equipment: Galitzin horizontal pendulum, mech. registr., two comp. Galitzin vertical-motion seismograph, mech. registr.

(COCOS) KEELING ISLANDS

The Milne seismograph formerly maintained at this station was destroyed by the German cruiser "Emden" on November 9, 1914, and has not been replaced.

Postal address: Superintendent, Eastern ExtensionTelegraph Company, Cocos Island, via Singapore.

$\varphi = 12°12'$ S., $\lambda = 96°54'$ E.

KEW, see RICHMOND

KINGSTON, JAMAICA

Private seismologic station inaugurated in 1907.
J. F. Brennan, Government Meteorologist, Proprietor.

Postal address: J. F. Brennan, Esq., Kingston, Jamaica.

$\varphi = 17°57'41''$ N., $\lambda = 76°47'40''$ W., h = (a) ca. 1.5 m.
(b) ca. 30.2 m.

Lithologic foundation: alluvium.

Equipment: Seismograph of Gray-Milne type.
Duplex pendulum seismograph.
Horizontal pendulum seismograph, local construction, two comp. N and E. Constants: $V = 1\ {}^{5}/_{18}$, $T_0 = 24$ sec., 1 mm. displacement = 1″, 1¼ inches = 1 hour.

Time service: time is kept by a pendulum clock of good rate. Time comparisons are made by sextant observations about once a fortnight.

*KLAUSTHAL, GERMANY

Seismologic Station, inaugurated in 1908.
Prussian Ministry of Education.

Postal address: Seismologic Station, Klausthal, Harz, Deutschland.

$\varphi = 51°48'30''$ N., $\lambda = 10°20'30''$ E.

Lithologic foundation: solid rock, in the abandoned tunnel of a mine at a depth of 600 m. below the surface.

Equipment: horizontal pendulum, mass 100 kg.

Time service: time is transmitted by telephone from Göttingen.

KOBE, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1904 (1910).

Y. Horiginti, Director.

Supported by the local prefecture.

Postal address: Kobe Meteorological Observatory, Kobe, Japan.

$\varphi=34^\circ 41'10''$ N., $\lambda=135^\circ 10'51''$ E., h=58.2 m.

Lithologic foundation: loam (diluvial series).

Equipment: Omori horizontal pendulum seismograph, two comp. N and E

Constants:		mass	V	T_0
	N,	18.5 kg.	20	19 sec.
	E,	17.5 "		

Time service: time marks made by a contact chronometer compared daily with the time ball of the Kobe Harbor Office; also time comparisons by direct telegraphic communication with the Tokyo Astronomical Observatory.

KODAIKANAL, S. INDIA

Seismologic Station, inaugurated January 12, 1900.

J. Evershed, Director of the Observatory.
Kodaikanal Observatory, Meteorological Department,
Government of India.

Postal address: Kodaikanal Observatory, Kodaikanal, South India.

$\varphi=10^\circ 13'50''$ N., $\lambda=77^\circ 28'00''$ E., h=2343 m.

Lithologic foundation: charnockite rock.

Equipment: Milne seismograph, E comp.
Constants: V=9.76, E=1.

Time service: Time is marked by the hourly eclipse of light by a watch compared daily with the standard observatory clock; time comparisons daily to within 0.1 sec. by signal from the Madras Observatory. Clock error is never greater than ±2 sec. Hour time marks are also made by an electromagnet in circuit with the standard clock. On the seismogram time can be read to within ±5 sec.

Publication: Data are published in the India Monthly Weather Review; also sent to the Brit. Ass. Seismological Committee.

*KOLOZSVAR, HUNGARY

Seismologic Observatory, inaugurated in 1912 (?).

Postal address: Seismologic Observatory, Kolozsvar, Hungary.

$\varphi = 46°41'16''$ N., $\lambda = 23°32'$ E., h = 340 m.

Equipment: Mainka horizontal pendulum, mass 210 kg., two comp.

*KÖNIGSBERG, PRUSSIA, GERMANY

Hauptstation für Erdbebenforschung[1], inaugurated in 1911.

Prof. Dr. A. Tornquist, Director.
Geologisches Institut.

Postal address: Hauptstation für Erdbebenforschung, Lange Reihe 4, Königsberg, Preussen, Deutschland.

$\varphi = 54°50'$ N., $\lambda = 20°30'$ E.

Lithologic foundation: heavy concrete base, in a specially constructed building, on sand and loam resting on rock (Cretaceous).

Equipment: Wiechert inverted pendulum, mass 1,000 kg., Wiechert vertical-motion seismograph.

Time service: the clock is checked by telephone from the Astronomical Observatory at Königsberg.

[1] 15 km. north of Königsberg.

*KÖNIGSTEIN i. T., GERMANY

Taunus Observatorium bei Königstein i. T.

Dr. F. Linke, Director.
Meteorologisch-Physikalisches Institut des Physikalisches Vereins, Frankfurt a. M.

Postal address: Taunus Observatorium, Königstein i. T., Deutschland.

$\varphi = 50°13'$ N., $\lambda = 8°27'$ E., h = 827 m.

Lithologic foundation: quartzite.

Equipment: Galitzin horizontal seismograph. Mainka horizontal seismograph, mass 450 kg. Wiechert vertical-motion seismograph, mass 80 kg.

KOSHUN, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1897.
Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi = 22°00'$ N., $\lambda = 120°44'$ E., h = 23.3 m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; also since October, 1907, Omori horizontal pendulum tromometer, mass 6 kg., E comp.
Constants: $V = 10$, $T_0 = 20$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

*KRAKOW, POLAND

Astronomical Observatory.
Prof. Dr. M. P. Rudski, Director.
University.

Postal address: Astronomical Observatory, University, Krakow, Poland.

$\varphi = 50°03'05.9''$ N., $\lambda = 19°57'04.5''$ E., h = ca. 205 m.

Lithologic foundation: compact sandy clay and alluvium.

Equipment: Bosch-Omori horizontal pendulum, mass 10 kg., two comp.

*KRASNOJARSK, SIBERIA, RUSSIA

Seismologic Station.

$\varphi = 56°01'$ N., $\lambda = 92°52'$ E.

Equipment: Bosch-Omori horizontal pendulum, two comp.

*KRASNOVODSK, SIBERIA, RUSSIA

Seismologic Station.

$\varphi = 39°59'$ N., $\lambda = 53°03'$ E.

KREMSMÜNSTER, AUSTRIA

This station has been discontinued.

Oberosterreich Sternwarte Kremsmünster.

$\varphi = 48°03.4'$ N., $\lambda = 14°07.9'$ E.

*KREMSMÜNSTER, AUSTRIA

Observatoire des Benedictines.[1]

Postal address: Observatoire des Benedictines, Kremsmünster, Österreich.

$\varphi = 48°03'$ N., $\lambda = 14°08'$ E., h = 380 m.

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[1] Service discontinued.

Lithologic foundation: ca. 20 m. of glacial till over stratified rock (Tertiary).

Equipment: Rebeur-Ehlert horizontal pendulum, three horizontal components.

KUMAMOTO, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1918.
S. Kuriyama, Director.
Supported by the local prefecture.

Postal address: Kumamoto Meteorological Observatory, Kumamoto, Japan.

$\varphi = 32°49'$ N., $\lambda = 130°42'$ E., $h = 37.9$ m.

Lithologic foundation: rock.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V = 50$, $T_0 = 3.6$ sec.; E, $V = 50$, $T_0 = 3.8$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

KYOTO, JAPAN

Kamigamo Geophysical Observatory[1], seismologic service inaugurated in 1908.
Prof. Toshi Shida, Director.
Imperial University of Kyoto.

Postal address: Geophysical Institute, Imperial University of Kyoto, Kyoto, Japan.

$\varphi = 35°03'33''$ N., $\lambda = 135°46'$ E., $h = 175$ m.

Lithologic foundation: rock (Paleozoic).

Equipment: Wiechert inverted pendulum, mass 1000 kg., two comp. N and E.
Constants: $V = 200$, $T_0 = 12$ sec., $\epsilon = 3$.
Wiechert vertical-motion seismograph, mass 1,300 kg., Z comp.
Constants: $V = 160$, $T_0 = 5$ sec., $\epsilon = 3$.
Rebeur-Paschwitz horizontal pendulum, for measuring earth body tides.
Omori horizontal pendulum, two comp. N and E: $V = 20$, $T_0 = 15$ sec.

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[1] The Imperial University of Kyoto maintains also a second order seismological station at Uji, ca. 20 km. south of the University. The data of this station were not given.

In preparation—
A 20-ton (20,000 kg.?) horizontal seismograph to have $V=2,000$.
Long-period horizontal pendulums.

Time service: hour and minute time marks are made by a pendulum clock compared daily by telephone with the Riefler standard clock of the Astronomical Observatory; time is accurate within one second.

KYOTO, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1916.
M. Tozima, Director.
Supported by the local prefecture.

Postal address: Kyoto Meteorological Observatory, Kyoto, Japan.

$\varphi=35°01'$ N., $\lambda=135°44'$ E., $h=41.5$ m.

Lithologic foundation: sandy clay.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: N, $V=50$, $T_0=4.5$ sec.; E, $V=50$, $T_0=4.0$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

*LAIBACH, JUGOSLAVIA

Seismologic Station, inaugurated in 1897.
Prof. Dr. A. Belar, Director.
Technical High School.

Postal address: Seismologic Station, Laibach, Jugoslavia.

$\varphi=46°03'$ N., $\lambda=14°31'$ E., $h=296$ m.

Lithologic foundation: alluvium.

Equipment: Galitzin aperiodic horizontal pendulum; Vicentini seismograph, two comp.; Grablovitz-Belar horizontal pendulum, two comp.; Rebeur-Ehlert seismograph, three comp.; horizontal pendulum, phot. registr.

LA PAZ, BOLIVIA

Estacion sismológica San Calixto, inaugurated in 1913.
Prof. P. M. Descotes, S.J., Director.
Colegio de San Calixto.

Postal address: Estacion Sismológica San Calixto, La Paz, Bolivia.

$\varphi=16°29'43''$ S., $\lambda=68°09'10''$ W., $h=3658$ m.

Lithologic foundation: old alluvium.

Equipment: and constants:	Mass	V	T_0
Bifilar horizontal pendulum, N comp.	2,000 kg.	180	14.0 sec.
“ “ “ E “	500 “	80	18.0 “
“ “ “ E “	100 “	25	20.0 “
Vertical (simple) “ N and E comp.	1,500 “	1,100	2.4 “

Time service: time is kept and time comparisons are made with the accuracy of the Astronomical Observatory service.

LA QUIACA, ARGENTINA

Observatorio La Quiaca, seismologic service inaugurated in July, 1917.
Observer subject to change,
Oficina Meteorológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi = 22°08'$ S., $\lambda = 65°43'$ W., $h = 3462$ m.

Lithologic foundation: volcanic.

Equipment: Milne seismograph, two comp. N and E.
Constants: $T_0 = 16$ sec.; N, 1 mm. displacement $= 0.54''$,
E, 1 “ “ $= 0.36''$.

Time service: light eclipsed once each hour; marks checked four or five times a day with a chronometer; time comparisons made occasionally by astronomical observations. Sun dial, with graphic correction curve, reading approximately to 1 to 5 seconds.

LA VALETTA, see MALTA

LAWRENCE, KANSAS

Seismographic Station, inaugurated earlier than 1910. Regular service from April 30, 1915.
Prof. Winthrop P. Haynes, in charge.
Department of Geology, University of Kansas.

Postal address: Seismographic Station, University of Kansas, Lawrence, Kansas.

$\varphi = 38°57'30''$ N., $\lambda = 95°14'58''$ W., $h = 301.1$ m.

Lithologic foundation: limestone.

Equipment: Wiechert inverted pendulum, two comp. N and E.
Constants: N, $V = 205$; E, $V = 177$; both, $T_0 = 3.4$ sec.. $\epsilon = 4$.

Time service: time is kept and hour and minute time marks are made electromagnetically by a contact pendulum clock compared daily by radiotelegraphic signals from Arlington.

LECCE, see TARANTO

*LEIPZIG, GERMANY

Erdbebenwarte der Universität, inaugurated in 1902.

Postal address: Erdbebenwarte, Universität, Leipzig, Deutschland.

$\varphi = 51°20'06''$ N., $\lambda = 12°23'30''$ E., h = 119 m.

Lithologic foundation: gravels (Pliocene).

Equipment: Wiechert inverted pendulum, mass 1,000 kg.

LE MANS (SARTHE), FRANCE

Seismologic Station, inaugurated in March, 1912.
Albert Jagot, in charge.
Privately inaugurated and conveyed to the city.
Postal address: Station sismologique, Beauverger 36, Le Mans, France.
$\varphi = 48°00'17''$ N., $\lambda = 0°12'30.6''$ E., h = 77 m.
Lithologic foundation: clay.
Equipment: horizontal pendulum, Mainka type, mass 300 kg., two comp. N and E.
Constants: N, V = 43, $T_o = 7$ sec.; E, V = 48, $T_o = 9$ sec.; 6 mm. = 1 min.
Records changed weekly.

Time service: time is kept and minute time marks are made by an accurate contact clock compared daily by radiotelegraphic signals from the Eiffel tower.

LILLE, FRANCE

Seismologic Station.
Prof. Chas. Barrois, Director.
University of Lille.

The station is temporarily disorganized as a consequence of the war. It is now in course of reorganization.

*LIMA, PERU

Observatorio Seismografico de la Sociedad Geografica de Lima.
H. Hope-Jones, Director.

Postal address: Observatorio Seismografico, Sociedad Geografica de Lima, Lima, Peru.

$\varphi = 12°03'05.8''$ S., $\lambda = 77°00'50''$ W., h = 154 (or 122?) m.

Lithologic foundation: differently given in available records as "gravel and conglomerate on andesite" and "alluvium on basement of diorite and metamorphic rocks": the seismograph is mounted on a pier of stone and cement which goes 10 feet into the ground.

Equipment: Milne seismograph, E comp.

LISBON, PORTUGAL

Seismologic Station, inaugurated in January, 1918.
General João Maria de Almeida Lima, Director.
Observatory "Infante D. Luis."

Postal address: Observatory "Infante D. Luis," Lisbon, Portugal.

$\varphi = 38°43'13''$ N., $\lambda = 9°08'20.5''$ E., h = 78 m.

Lithologic foundation: marls.

Equipment: Wiechert inverted pendulum, mass 1,000 kg.
Constants: L = 36 m., I = 8,571, V = 238, $T_0 = 12$ sec., $\epsilon = 7.8$, r = 0.75.
Wiechert vertical-motion seismograph, mass 1,300 kg., not yet in use.
Mainka horizontal seismograph.
Agamennone seismograph.

Time service: time comparisons by telephone from the Astronomical Observatory of Lisbon.

LIVERPOOL (BIDSTON-BIRKENHEAD), ENGLAND

Liverpool Observatory, seismologic service inaugurated in 1898.
William E. Plummer, Director.
Mersey Docks and Harbour Board.

Postal address: Liverpool Observatory, Bidston-Birkenhead, England.

$\varphi = 53°24'04.8''$ N., $\lambda = 3°04'19.5''$ W., h = ca. 56 m.

Lithologic foundation: sandstone (Kuyper).

Equipment: Milne seismograph, N comp.
Milne-Shaw seismograph, N comp., constants not stated.

Time service: time is kept by a clock electrically controlled (by a master-clock?); time comparisons are made by radiotelegraphic signals.

LIVORNO, ITALY

Osservatorio sismico, inaugurated in June, 1914.
Prof. Giuseppe Schiavazhi, Director.

Postal address: Osservatorio Sismico, Livorno, Italia.

$\varphi = 43°31'38.26''$ N., $\lambda = 10°18'23.89''$ E., h = sea level.

Lithologic foundation: sandy rock.

Equipment: Stiattesi, Vicentini, and Schiavazhi seismographs.

Time service: mean time chronometer.

LWÓW (LEMBERG), POLAND

Seismologic Station, inaugurated in June, 1899.

Prof. Dr. L. Grabowski, Director.

Technical High School.

Postal address: Observatory of the Technical High School, Lwów (Lemberg), Poland.

$\varphi = 49°50'11''$ N., $\lambda = 24°01'$ E., $h = 312$ m.

Lithologic foundation: 5 m. sand and sandstone (diluvial and Tertiary) resting on compact marl (Cretaceous).

Equipment: Bosch-Omori horizontal pendulum, two comp. N and E.

Constants: $V =$ ca. 10, $T_0 = 30$ sec., $\epsilon_N =$ ca. 5. $\epsilon_E =$ ca. 3.

Time service: minute time marks are made electromagnetically by a contact pendulum clock checked twice a week with the standard clock of the Observatory; time comparisons are made by meridian transit observations very accurately (average probable error ca. 0.05 sec.); the time of a sharply marked disturbance on the seismogram can be determined with an accuracy of about 1 sec.

MADRAS, see KODAIKANAL

MAEBASHI, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1912.

K. Akaii, Director.

Supported by the local prefecture.

Postal address: Maebashi Meteorological Observatory, Maebashi, Japan.

$\varphi = 36°24'$ N., $\lambda = 139°04'$ E., $h = 111.7$ m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.

Constants: $V = 100$, $T_0 = 4.1$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

*MAHE, SEYCHELLES

Seismologic Station, inaugurated in 1911.

Eastern, Eastern Extension and Pacific Telegraph Co.

Postal address: Seismologic Station, Mahe, Seychelles.

$\varphi=4°05'$ S., $\lambda=55°05'$ E.,

Equipment: Milne seismograph, E comp.

*MAKEJEVKA, RUSSIA

Seismologic Station, a station of the first class of the Russian Service. The Society of Mine Industries of South Russia.

Postal address: Seismologic Station, Makejevka, Russia.

$\varphi=48°02'$ N., $\lambda=37°59'$ E.

Equipment: Galitzin seismographs.

The instruments are mounted in a specially constructed building.

MALABAR, NETHERLANDS EAST INDIES

Seismologic Station.
$\varphi=7°13'$ S., $\lambda=107°37'$ E.,

Equipment: Wiechert inverted pendulum, mass 100 kg., two comp. N and E.

MALAGA, SPAIN

Estación Sismológica de Málaga.
D. José Rodríguez de Córdoba, Ingeniero Geógrafo, Director.
Instituto Geográfico y Estadístico.

Postal address: Ingeniero Jefe de la Estación Sismológica de Málaga, España.

$\varphi=36°43'39''$ N., $\lambda=4°24'40.5''$ W., h=60 m.

Lithologic foundation: quartzose limestone.

Equipment: and constants:		Mass	V	T_o	r/T_o^2	m. per hour
Bosch-Omori seismograph,	N comp.	25 kg.	14	17.0	0.005	0.9
“ “ “	E “	25 “	15	16.0	0.008	0.9
Vicentini “	N “	100 “	110	2.4	0.010	0.6
“ “	E “	100 “	110	2.3	0.010	0.6
“ “	Z “	50 “	120	0.9	0.020	0.6

An Agamennone seismoscope.

Time service: time is kept and minute time marks are made electromagnetically by a Bosch contact clock compared by radiotelegraphic signals from the Eiffel tower.

ISLAND OF MALTA

Meteorological Observatory, seismologic service inaugurated May 10, 1906.

Prof. Thomas Agius, Director.
Malta University.

Postal address: Seismological Station, Meteorological Observatory, University, Malta.

$\varphi = 35°52'48''$ N., $\lambda = 14°30'50''$ E., h = ca. 36.9 m.

Lithologic foundation: limestone.

Equipment: Milne seismograph, E comp.

Time service: time marks made by eclipse of light by an excellent clock checked daily by the Admiralty Time-ball.

MAMBAJAO, CAMIGUIN ISLAND, PHILIPPINE ISLANDS

Meteorological Station, seismologic service inaugurated in March, 1917.

Domingo Araw, Observer.
Weather Bureau, Philippine Islands.

Postal address: The Meteorological Station, Mambajao, Misamis, P. I., or Manila Observatory, Manila, P. I.

$\varphi = 9°15'$ N., $\lambda = 124°43'$ E., h = 6.5 m.

Lithologic foundation: extrusive rock.

Equipment: Vicentini system, Manila type.

Time service: time comparisons daily by telegraphic signals; no chronograph.

MANILA, PHILIPPINE ISLANDS

Manila Observatory, seismologic service inaugurated in 1884.

Miguel Saderra Masó, Chief, Seismic and Magnetic Divisions, Weather Bureau, Philippine Islands.
Chief Station of the Philippine Service.

Postal address: Manila Observatory, Philippine Islands.

$\varphi = 14°34'41''$ N., $\lambda = 120°58'33''$ E., h = 3 to 10 m.

Lithologic foundation: alluvial and littoral deposits.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.
Constants: N, $T_0 = 6.25$ sec., $\epsilon = 2.906$; E, $T_0 = 6.18$ sec., $\epsilon = 2.393$.
Vicentini system, Padova type.
Bertelli tromometer.

Cecchi seismograph.
Gray-Milne seismograph.
Omori system, Manila type.

Time service: time comparisons made daily with the standard clocks o the Observatory in the same building.

*MARITUJ, RUSSIA

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 51°46'$ N., $\lambda = 104°07'$ E.

Equipment: Wiechert inverted pendulum, small model.

MARSEILLES, FRANCE

Observatoire de Marseille, seismologic service inaugurated in 1909.
Prof. Bourget, Director.
Université de Marseille.

Postal address: Observatoire de Marseille, Marseille, France.

$\varphi = 43°18'19''$ N., $\lambda = 5°23'38''$ E., h = 75 m.

Lithologic foundation: limestone.

Equipment: Mainka horizontal pendulum, mass 130 kg., two comp.

Time service: city circuit of (electric) synchronous clocks correct to 0.2 sec.; time comparisons made by meridian circle observations.

MATSUMOTO, JAPAN

Meteorological Observatory, seismologic service inaugurated in April, 1917.
I. Yanagisawa, Director.
Supported by the local prefecture.

Postal address: Matsumoto Meteorological Observatory, Matsumoto, Japan.

$\varphi = 36°14'$ N., $\lambda = 137°59'$ E., h = 581 m.

Lithologic foundation: alluvium (loam).

Equipment: C. M. O. horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V = 20$, $T_0 = 10$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

MATSUYAMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1911.

K. Hiroe, Director.

Supported by the local prefecture.

Postal address: Matsuyama Meteorological Observatory, Matsuyama, Japan.

$\varphi = 33°50'$ N., $\lambda = 132°45'$ E., $h = 31.4$ m.

Lithologic foundation: granitic gravel, soil.

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.

Constants: $V = 100$, $T_0 = 12$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

MAZATLÁN (SINALOA), MEXICO

Estación Seismológica de Mazatlán, a station of the second order.

Pablo Vazquez Schiaffino, Jefe de la Estación.

Servicio Seismológico Nacional de México,
Instituto Geológico Nacional.

Postal address: Instituto Geológico Nacional, 6a del Cipres núm. 176, México, D. F., República Mexicana.

$\varphi = 23°11'17''$ N., $\lambda = 106°23'38''$ W., $h = 70$ m.

Lithologic foundation: andesitic porphyry.

Equipment: Wiechert inverted pendulum, mass 200 kg., two comp. N and E. Wiechert vertical-motion seismograph, mass 80 kg., Z comp.

Time service: time comparisons by telegraphic signals from Tacubaya.

MELBOURNE, see SOUTH YARRA

MENDOZA, ARGENTINA

Escuela Vitivinícola, seismologic service inaugurated in February, 1916.

Observer subject to change.

Oficina Meteorológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi = 32°53'$ S., $\lambda = 68°49'$ W., $h = 755$ m.

Lithologic foundation: alluvial.

Equipment: Milne seismograph, N comp.
Constants: $T_0 = 14$ sec., 1 mm. displacement = 0.49″.

Time service: light eclipsed once each hour; marks checked four or five times a day with a chronometer compared once or twice a week by telegraphic signals sent to the local post-office. "Accuracy not very great."

MERIDA (YUCATAN), MEXICO

Seismologic Station, of the first order.
Rafael Acosta Ocampo, Jefe de la Estación.
Servicio Seismológico Nacional de Mexico,
Instituto Geológico Nacional.

Postal address: Instituto Geológico Nacional, 6a del Cipres núm. 176, México, D. F., República Mexicana.

$\varphi = 20°56'52''$ N., $\lambda = 89°37'$ W., $h = 6.35$ m.

Lithologic foundation: limestone (Quaternary).

Equipment: Wiechert inverted pendulum, mass 1,200 kg., two comp. N and E. Wiechert vertical-motion seismograph, mass 1,300 kg., Z comp.

Time service: time comparisons by telegraphic signals from Tacubaya.

MESSINA, ITALY

Osservatorio Geofisico di Messina, seismologic service inaugurated December 1, 1902 (this observatory continues the work of an older establishment).

Prof. Dr. Comm. G. B. Rizzo, Director.
University.

Postal address: Osservatorio Geofisico di Messina, Italia.

$\varphi = 38°12'$ N., $\lambda = 15°33'$ E., $h = 48.8$ m.

Lithologic foundation: sandstone.

Equipment: Vicentini microseismograph, mass 100 kg., three comp.

Constants:	V	T_0
NE and NW comp.,	100	2.4 sec.
Z "	120	0.9 "

Conrad seismograph, mass 26 kg., one comp NW, $T_0 = 1.8$ sec.
Horizontal pendulum seismograph, mass 100 kg., two comp. NE and NW, with electromagnetic damping.

Constants:	V	T_0	ϵ
NE comp.,	50	26 sec.	1.2
NW "	50	25.5 "	1.2

Time service: time is kept by a Cooke sidereal clock and by a Riefler mean time clock; time determinations are made by transit observations.

MEXICO, see TACUBAYA

MILAN, LOMBARDY, ITALY

Seismologic Station, inaugurated in June, 1909.
L. Gabba, Director.
Reale Osservatorio Astronomico di Brera.

Postal address: Reale Osservatorio Astronomico di Brera, Milano, Lombardia, Italia.

$\varphi = 45°27'59.3''$ N., $\lambda = 9°11'29.7''$. E., $h = 124$ m.

Lithologic foundation: alluvial ground.

Equipment: Agamennone seismograph, mass 210 kg., length 6.59 m., two comp. N and E.
Constants: $V =$ ca. 20, $T_0 = 2.6$ sec., ca. 60 cm. = 1 hour.
Galli seismograph.
Cecchi seismic alarm.

Time service: minute time marks are made electromagnetically by a contact clock; accuracy ca. 2 sec.

*MILETO, CATANZARO, ITALY

Osservatorio Sismico "Morabito" nel Seminario.

Postal address: Osservatorio Sismico "Morabito" Mileto, Catanzaro, Italia.

$\varphi = 38°36'14''$ N., $\lambda = 16°03'14''$ E., $h =$ ca. 360 m.

Equipment: Omori seismograph, mass 200 kg.
Constants: $V = 25$, $T_0 = 20$ sec., 100 cm. = 1 hour.

Time service: time is determined by meridian transit observations.

MILWAUKEE, WISCONSIN

Seismologic Station, inaugurated in 1909.
John B. Kremer, in charge, temporarily.
Marquette University.

Postal address: Marquette University, Milwaukee, Wisconsin.

$\varphi = 43°32'$ N., $\lambda = 87°50'40''$ W.,

Lithologic foundation: concrete pier, free of floor, on limestone.

Equipment: Wiechert inverted pendulum, mass 80 kg., not completely installed.

Time service: contact clock (Wiechert).

MINEO (CATANIA), ITALY

Osservatorio Meteorico Geodinamico "Guzzanti," seismologic service inaugurated in 1885.
Prof. Comm. Corrado Guzzanti, Director.
Privately established.

Postal address: Osservatorio Meteorico Geodinamico "Guzzanti," Mineo (Catania), Italia.

$\varphi = 37°15'$ N., $\lambda = 14°44'$ E., h = 509.85 m.

Lithologic foundation: (Pliocene).

Equipment: Guzzanti horizontal seismograph, mass 200 kg., two comp., length of pendulum, 2.80 m.
Constants: $V = 20$, $T_o = 3.0$ sec., 80 cm. = 1 hour.
Agamennone horizontal seismograph, mass 50 kg., two comp.
Constants: $V = 30$, $T_o = 8$ sec., 1.3 m. = 1 hour.
Brassart seismograph, mass 20 kg., three comp.
Constants: length = 2.35 m., $V = 13$, $T_o = 2$ min. 33 sec., 0.24 m. = 1 hr.
Several subordinate seismographic devices.

Time service: not stated.

MITO, JAPAN

Meteorological Observatory, seismologic service inaugurated in April, 1905.
H. Uno, Director.
Supported by the local prefecture.

Postal address: Mito Meteorological Observatory, Mito, Japan.

$\varphi = 36°23'$ N., $\lambda = 140°28'$ E., h = 30 m.

Lithologic foundation: hilly ground.

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.
Constants: N, $V = 20$, $T_o = 38.7$ sec.; E, $V = 20$, $T_o = 29.8$ sec.

Time service: time comparisons daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

MIYAZAKI, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1915.

Y. Satake, Director.

Supported by the local prefecture.

Postal address: Miyazaki Meteorological Observatory, Miyazaki, Japan.

$\varphi=31°55'$ N., $\lambda=131°26'$ E., h=6.8 m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.

Constants: N, $V=50$, $T_0=2.8$ sec.; E, $V=50$, $T_0=3.0$ sec.

Time service: time comparisons are obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

MIZUSAWA, JAPAN

International Latitude Observatory, seismologic service inaugurated in January, 1911.

A. Kimura, Director.

Postal address: International Latitude Observatory of Mizusawa, Iwate-ken, Japan.

$\varphi=39°08'03.6''$ N., $\lambda=141°07'41''$ E., h=61.0 m.

Lithologic foundation: (Quaternary).

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.

Constants: N, $V=20$, $T_0=36$ sec.; E, $V=100$, $T_0=16$ sec.

Time service: of the International Latitude Observatory; time marks made by a contact chronometer; time comparisons based on astronomical observations.

MOBILE, see SPRING HILL

MONCALIERI, ITALY

Osservatorio sismico, inaugurated in 1905.

Dr. Giovanni Penta, Director.

Real Collegio Carlo Alberto.

Postal address: Osservatorio sismico, Moncalieri, Italia.

$\varphi=44°59'51.8''$ N., $\lambda=7°41'43.1''$ E., h=238 m.

Lithologic foundation: alluvial.

Equipment: and constants:	Mass	V	T_0
Stiattesi horizontal pendulum, N comp.	260 kg.	34	19.4 sec.
" " " E "	260 "	34	20.3 "
Vertical (simple) "	650 "	58	3.2 "

100 cm. = 1 hour.
Two small horizontal pendulums with electric contacts to give alarm.

Time service: time is kept and minute time marks are made directly with the writing styles by means of a good contact clock; every day radiotelegraphic signals from the Eiffel tower are marked directly on the records by the styles; the accuracy of reading of the seismograms is ca. 1 sec.

MONTECASSINO (CASERTA), ITALY

Osservatorio Meteorico-Aerologico-Geodinamico, seismologic service inaugurated in 1875.
Dr. Bernardo M. Paoloni, O.S.B., Director.
R. Ufficio Centrale di Meteorologia e Geodinamica, Roma.

Postal address: Osservatorio Meteorico-Aerologico-Geodinamico, Montecassino (Caserta), Italia.

$\varphi = 41°29'26''$ N., $\lambda = 13°49'07''$ E., h = 540 m.

Lithologic foundation: not stated.

Equipment: Cancani seismograph, three comp. Agamennone seismograph, three comp.
Constants: see "La Meteorologia Pratica, No. 1, 1920."
Several subordinate seismographic mechanisms.

Time service: time is kept (and marked?) by marine chronometers compared daily by radiotelegraphic signals from the Eiffel tower.

MONTEVIDEO, URUGUAY

Observatorio Central del Instituto Nacional Físico-Climatológico, seismologic service inaugurated in 1909.
Prof. Luis Morandi, Director.
Dependencia del Ministerio de Industrías.

Postal address: Instituto Nacional Físico-Climatológico, Montevideo-Prado, Uruguay.

$\varphi = 34°51'47.7''$ S., $\lambda = 56°12'05.5''$ W., h = 25 m.

Lithologic foundation: heavy masonry pier, free of floor and 1 m. from walls, on clay.

Equipment: Vicentini microseismograph, mass 65 kg., two comp. N and E. (simple pendulum).
Constants: length of pendulum = 1.6 m., V = 112.
Alfani horizontal seismograph, mass 45 kg., two comp. NE and NW.
Constants: NE, V = 120, $T_0 = 13.8$ sec.; NW, V = 120, $T_0 = 18.8$ sec.

Time service: time is kept and minute time marks are made electromagnetically by a clock having an invar pendulum, compared once a day by means of a signal from the office of the Time Service.

*MOSCOW, RUSSIA

Seismologic Station.
Dr. Ernest Leyst, Director.
Imperial University.

$\varphi = 55°45'$ N., $\lambda = 37°34'$ E.

Lithologic foundation: sand.

Equipment: Bosch-Omori horizontal pendulum, two comp.

MOUNT HAMILTON, CALIFORNIA

Lick Observatory, seismologic service inaugurated in 1887; with present equipment May 23, 1911.
Dr. W. W. Campbell, Director of the Observatory.
Lewis A. Bond (Berkeley), in charge of seismometric measurement.
University of California.

Postal address: Lick Observatory, Mt. Hamilton, California, or Seismographic Station, University of California, Berkeley, Calif.

$\varphi = 37°20'24.5''$ N., $\lambda = 121°38'34''$ W., $h = 1281.7$ m.

Lithologic foundation: feldspathic sandstone.

Equipment: and constants:		V	T_0	ϵ
Wiechert, mass 80 kg.,	N and E comp.,	100	6	0.25
" " 80 "	Z "	60	3	0.25
Duplex-pendulum seismograph,		5	2.5	
Ewing three-component seismograph,	N "	4	5	
" " " "	E "	4	5	
" " " "	Z "	3	3	

Time service: with the Wiechert seismographs hour and minute time marks are made electromagnetically by a compensated contact clock whose accuracy (=rate) is ca. 0.3 sec. per day compared two or three times a week with the standard clocks of the Observatory which are of a very high order of accuracy.

MUKAIYAMA, JAPAN

Observatory of Mukaiyama, seismologic service inaugurated in 1913.
Prof. Sirota Kusakabé, Director.
Tôhoku Imperial University.

Postal address: Observatory of Mukaiyama, Sendai, Japan.

$\varphi=38^\circ14'38.8''$ N., $\lambda=140^\circ51'56.3''$ E., h = 88 m.

Lithologic foundation: loam.

Equipment: Omori horizontal pendulum, N comp., V = 120.
E " V = 20.
Omori vertical-motion seismograph, Z comp., V = 10.
Imamura horizontal seismograph, N comp., V = 2; E comp., V = 2.
Wiechert inverted pendulum, two comp. N and E, V = 100.
Wiechert vertical-motion seismograph, Z comp., V = 280.

Time service: chronometer, error ca. 1 sec., checked by astronomical observations.

MUNICH, GERMANY

Erdbebenwarte München, inaugurated in 1905.
Prof. Dr. C. W. Lutz, Director.
Sternwarte München u. Verwaltung d. wiss. Sammlungen d. Staates.

Postal address: Erdbebenwarte München 27, Sternwarte, Bayern, Deutschland.

$\varphi=48^\circ08'46''$ N., $\lambda=11^\circ36'31''$ E., h = 528 m.

Lithologic foundation: glacial detritus.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E. 15 mm. = 1 minute.

Time service: daily chronographic comparisons with the chief clock of the Astronomical Observatory; accuracy ca. 0.1 sec.

NAHA, JAPAN

Meteorological Observatory, seismologic service inaugurated in November, 1912.
T. Tsutsui, Director.
Supported by the Okinawa prefecture.

Postal address: Naha Meteorologial Observatory, Naha, Okinawa-ken, Japan.

$\varphi=26^\circ13'$ N., $\lambda=127^\circ41'$ E., h = 8.9 m.

Lithologic foundaton: limestone.

Equipment: Omori horizontal pendulum tromometer, E comp. Constants: V = 120, $T_0=6$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

NAGANO, JAPAN

Meteorological Observatory, seismologic service inaugurated in July, 1903.

Z. Nishizawa, Director.

Supported by the local prefecture.

Postal address: Nagano Meteorological Observatory, Nagano, Japan.

$\varphi = 36°40'$ N., $\lambda = 138°12'$ E., h = 418.1 m.

Lithologic foundation: diluvial hill.

Equipment: and constants:		V	T_0
Omori horizontal pendulum tromometer,	E comp.,	15	39.7 sec.
" " " tremor recorder,	N "	100	4.0 "
" " " " "	E "	100	4.0 "

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

NAGASAKI, JAPAN

Meteorological Observatory, seismologic service inaugurated in April, 1913.

Dr. I. Goto, Director.

Supported by the local prefecture.

Postal address: Nagasaki Meteorological Observatory, Nagasaki, Japan.

$\varphi = 32°44'01''$ N., $\lambda = 129°52'37''$ E., h = 130.6 m.

Lithologic foundation: volcanic agglomerate.

Equipment: and constants:		V	T_0
Omori horizontal pendulum tromometer,	N comp.,	20	20 sec.
" " " "	E "	120	20 "
Imamura seismograph,	N "	2.0	7.0 "
" "	E "	2.0	7.0 "
Omori horizontal pendulum seismograph,	N "	5	6 "
" " " "	E "	5	6 "
" " " "	Z "	10	6 "

Time service: time marks are made by a contact chronometer; time comparisons are obtained by telephone from the office of the Nagasaki Time-Ball service.

NAGOYA, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1910.

R. Iguchi, Director.

Supported by the local prefecture.

Postal address: Aishi-ken Meteorological Observatory, Nagoya, Japan.

$\varphi = 35°10'$ N., $\lambda = 136°55'$ E., h = 15.2 m.

Lithologic foundation: concrete pier on soft soil (Quaternary).

Equipment: and constants:

		V	T_0
Omori horizontal pendulum tromometer,	N comp.,	50	15 sec.
" " " "	E "	50	15 "
C. M. O. " " tremor recorder,	N "	25	11 "
" " " " " " "	E "	25	8 "
Gray-Milne " "	N "	5	3 "
" " " "	E "	5	3 "

Time service: time is kept by two chronometers "adjusted" daily; time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*NAPLES, ITALY

Instituto di Fisica Terrestre[1] della R. Università.

Postal address: San Marcellino, Napoli, Italia.

$\varphi = 40°50.8'$ N., $\lambda = 14°15'36''$ E., h = 24.5 m.

VALLE DI POMPEI (NAPLES), ITALY

Osservatorio geodinamico-meteorico Pio X, seismologic service inaugurated 19 May, 1907.

Prof. Giovanni Alfano, Director.

Santuario Valle di Pompei, Napoli.

Postal address: Osservatorio, Valle di Pompei, Napoli, Italia.

$\varphi = 40°44'50''$ N., $\lambda = 14°30'06.9''$ E., h = 12.1 m.

Lithologic foundation: ashes and tuffs of Vesuvius.

Equipment and constants:

	mass	comp.	V	T_0	mm. per sec.
Omori-Alfani tromometrograph..	225 kg.	N	80	10	0.26
" " "	225	E	80	10	0.26
Microsismografo Vesuvio	500	NW	270	2.5	1.50
Navarro-Neumann pendulum .	850	E	320	1.9	0.30
Mercalli pendulum.............	500	N	270	2.0	1.80
Grablovitz pendulum	10	N	6	13.0	0.26
" "	10	E	6	20.0	0.26

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[1] Discontinued (?)

	mass	comp.	V	T_0	mm. per sec.
Grablovitz vasca	1,000	N	140	1.0	0.73
" - "	1,000	E	140	1.0	0.73
Denza macroseismograph.......	10	N	4	3.0	1.26
" "	10	E	4	3.0	1.26
Alfani Ortosismografo	200	Z	200	1.9	0.26

Time service: time is furnished by a clock with an invar pendulum and by a chronometer; time comparisons are made by telephone with the clocks of the Astronomical Observatory at Naples.

NEUCHATEL, SWITZERLAND

Station sismique, inaugurated in 1911.
Dr. Louis Arnot, Director.
Observatoire de Neuchatel.

Postal address: Station Sismique, Observatoire de Neuchatel, Schwyz.

$\varphi = 46°59'51''$ N., $\lambda = 6°55'48.5''$ E., h = 488 m.

Lithologic foundation: compact rock.

Equipment: Mainka bifilar horizontal pendulum, mass 146 kg., two comp. N and E.
Constants: N, V = 46, $T_0 = 7.2$ sec.; E, V = 65, $T_0 = 6.1$ sec., 30 mm. = 1 minute.

Time service: time is kept and marked by a contact precision clock; time comparisons are made by meridian circle observations with an accuracy of some hundredths of a sec.

NEW HAVEN, CONNECTICUT

Seismologic Station of Yale University.

Operation temporarily suspended.

NEW ORLEANS, LOUISIANA

Seismologic Station, inaugurated in 1910.
Rev. A. L. Kunkel, S.J., Director.
Nicholas D. Burke Observatory, Loyola University.

Postal address: Seismologic Station, Loyola University, New Orleans, Louisiana.

$\varphi = 29°56'54''$ N., $\lambda = 90°07'12''$ W., h = 2 m.

Lithologic foundation: alluvial.

Equipment: Wiechert inverted pendulum, mass 80 kg., two comp. N and E. Wiechert vertical-motion seismograph, mass 80 kg., Z comp.

Constants: V = 120, $\epsilon = 5$.

Time service: astronomical clocks.

FORDHAM, NEW YORK CITY, NEW YORK

Seismologic Station, inaugurated in November, 1910.

Joseph Lynch, S. J., Director.

Fordham University.

Postal address: Seismologic Station, Fordham University, Fordham, New York, New York.

$\varphi = 40°51'47''$ N., $\lambda = 73°53'08''$ W., h = 23.86 m.

Lithologic foundation: dolomite (Silurian, Stockbridge).

Equipment: Wiechert inverted pendulum, mass 80 kg., two comp. N and E.

Constants: V = 80, $T_0 = 7$ sec., $\epsilon = 5$.

Time service: time is kept and hour and minute time marks are made electromagnetically by a Wiechert contact clock; time comparisons are made by radiotelegraphic signals from Arlington.

NEW YORK, NEW YORK

Seismologic Station, inaugurated in June, 1912.

Chester A. Reeds, Observer in Charge, 1921.

New York Academy of Sciences, American Museum of Natural History.

Postal address: American Museum of Natural History, 77th Street and Central Park West, New York, New York.

$\varphi = 40°46'48.06''$ N., $\lambda = 73°58'39.60''$W., h = 26.206 m.

Lithologic foundation: mica schist.

Equipment: Mainka horizontal pendulum, mass 450 kg., two comp. N and E.

Constants: N, V = 95.5, $T_0 = 7.5$ sec.; E, V = 107, $T_0 = 7.5$ sec., air damping, ratio not stated.

Time service: time comparisons by radiotelegraphic signals from Brooklyn and Arlington; interrupted by the war, soon to be resumed.

*NICOLAJEF, RUSSIA

Observatoire Astronomique Maritime[1], seismologic service inaugurated in 1898.

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[1] This station probably was discontinued before the war.

$\varphi = 46°58.4'$ N., $\lambda = 31°58'27''$ E. (or $31°47.25'$?), h = 50 m.

Equipment: von Rebeur-Paschwitz horizontal pendulum.

NIIGATA, JAPAN

Meteorological Observatory, seismologic service inaugurated in August, 1912.

T. Sasaki, Director.
Supported by the local prefecture.

Postal address: Niigata Meteorological Observatory, Niigata, Japan.

$\varphi = 37°55'$ N., $\lambda = 139°03'$ E., h = 24.5 m.

Lithologic foundation: soft sandy hill.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V = 30$, $T_0 = 2.7$ sec.

Time service: time corrections obtained daily by radiotelegraphic signals from Tokyo Astronomical Observatory.

NÖRDLINGEN, GERMANY

Erdbebenwarte Nördlingen[1], inaugurated in June, 1911.

Otto Aumüller, Wissenschaftl. Leiter, in charge.
Sternwarte München.

Postal address: Erdbebenwarte Nördlingen, Bayern, Deutschland.

$\varphi = 48°50'55''$ N., $\lambda = 10°29'26''$ E., h = 432 m.

Lithologic foundation: limestone.

Equipment: Mainka bifilar horizontal pendulum, mass 465 kg., E comp. only. 15 mm. = 1 minute.

Time service: time comparisons are made by daily telegraphic signals from the Astronomical Observatory at Munich.

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[1] This is a sub-station of the station at Munich.

NORTHFIELD, VERMONT

Local Office, U. S. Weather Bureau, seismologic service inaugurated January 1, 1915.

W. A. Shaw, Meteorologist, in charge.
United States Weather Bureau.

Postal address: Local Office, U. S. Weather Bureau, Northfield, Vermont, or U. S. Weather Bureau, Washington, D. C.

$\varphi = 44°10'$ N., $\lambda = 72°41'$ W., h = 256 m.

Lithologic foundation: clay over bed rock.

Equipment: Bosch-Omori horizontal pendulum, mass 25 kg., two comp. N and E, mech. registr.

Constants: N, $V=10$, $T_0=16$ sec.; E, $V=10$, $T_0=15$ sec.

Time service: time is kept and minute time marks are made electromagnetically by a contact clock (Howard) compared daily with the telegraphic time signals of the Western Union service through the local office. The accuracy is dependent only on the time signals.

NUMAZU, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1915.
R. Kanada, Director.
Supported by the local prefecture.

Postal address: Numazu Meteorological Observatory, Numazu, Japan.

$\varphi=36°06'$ N., $\lambda=138°51'$ E., $h=6$ m.

Lithologic foundation: soft soil.

Equipment: C. M. O. horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V=20$, $T_0=5$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

OAXACA, MEXICO

Estación Seismológica de Oaxaca, a station of the second order.
Ignacio Gomez Feria, Jefe de la Estación.

Servicio Seismológico Nacional de México

Instituto Geológico Nacional.

Postal address: Instituto Geológico Nacional, 6a del Cipres núm. 176, México, D. F., República Mexicana.

$\varphi=17°01'$ N., $\lambda=96°47'$ W., $h=1{,}570$ m.

Lithologic foundation: volcanic tuff.

Equipment: Wiechert inverted pendulum, mass 200 kg., two comp. N and E. Wiechert vertical-motion seismograph, mass 80 kg., Z comp.

Time service: time comparisons by telegraphic signals from Tacubaya.

ÓGYALLA, see STARÁ ĎALA

OITA, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1906.

G. Yamagawa, Director.

Supported by the local prefecture.

Postal address: Oita Meteorological Observatory, Oita, Japan.

$\varphi = 33°14'$ N., $\lambda = 131°37'$ E., h = 4.5 m.

Lithologic foundation: soft ground.

Equipment: and constants:		V	T_0
Omori horizontal pendulum tromometer,	E comp.,	20	25 sec.
“ “ “ tremor recorder,	N “	90	6 “
“ vertical-motion tromometer,	Z “	20	10 “
C. M. O. horizontal pendulum tremor recorder,	N “	50	9 “
“ “ “ “ “ “ “	E “	50	9 “

Time service: time marks are made by a contact chronometer; time comparisons are obtained by radiotelephone from the Tokyo Astronomical Observatory.

OSAKA, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1901.

N. Shimono, Director.

Supported by the local prefecture.

Postal address: Osaka Meteorological Observatory, Osaka, Japan.

$\varphi = 34°39'$ N., $\lambda = 135°26'$ E., h = 1.5 m.

Lithologic foundation: soft soil.

Equipment: and constants:		V	T_0
Omori horizontal pendulum tromometer,	N comp.,	120	25 sec.
“ “ “ “	N “	20	30 “
“ “ “ “	E “	20	30 “
“ vertical-motion seismograph,	Z “	20	5 “
“ horizontal pendulum tremor recorder,	N “	60	5 “
“ “ “ “ “	E “	60	5 “
“ strong-motion seismograph,	N “	1	5 “
“ “ “ “	E “	1	5 “
“ “ “ “	Z “	2	5 “

Time service: time comparisons by direct telegraphic communication with the Tokyo Astronomical Observatory.

OSORNO, CHILE

Seismologic Station, a station of the second class of the Chilean service.

Postal address: Servicio Sismolójico de Chile, Santiago, Chile.

$\varphi = 40°35'$ S., $\lambda = 73°10'$ W., h = 25 m.

Lithologic foundation: alluvial.

Equipment: Wiechert inverted pendulum, mass 180 kg.

Time service: Time is kept and minute time marks are made by a contact clock compared weekly by telegraphic signals from the central station at Santiago.

ŌTOMARI, JAPAN

Meteorological Observatory, seismologic service inaugurated in January, 1911.

T. Noda, Director.

Supported by the Karafuto government.

Postal address: Karafuto Meteorological Observatory, Ōtomari, Karafuto, Japan.

$\varphi = 46°39'$ N., $\lambda = 142°46'$ E., h = 35.7 m.

Lithologic foundation: tuff (Tertiary).

Equipment: Omori horizontal pendulum tromometer, two comp. N and E.

Constants: N, $V = 20$, $T_0 = 28$ to 31 sec.; E, $V = 60$, $T_0 = 27$ to 30 sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

OTTAWA, CANADA

Seismologic Station, inaugurated in 1906.

Ernest A. Hodgson, Seismologist, in charge.

Dominion Observatory, Department of Interior, Government of Canada.

Postal address: Seismologic Station, Dominion Observatory, Ottawa, Canada.

$\varphi = 45°23'38''$ N., $\lambda = 75°42'57''$ W., h = 83 m.

Lithologic foundation: boulder clay over limestone (Cambro-Silurian).

Equipment: Bosch horizontal pendulum, two comp. N and E.

Constants: N, $V = 120$, $T_0 = 8.0$ sec.; E, $V = 120$, $T_0 = 7.1$ sec.

Wiechert vertical motion seismograph, Z comp.

Constants: $V = 120$, $T_0 = 6.3$ sec.

Undagraph, used in the investigation of microseisms (installed at Duncan's Cove, Chebucto Hd., near Halifax).
Deformation Instrument of the International Seismological Ass'n.

Time service: of the Dominion Observatory, minute contacts controlled by the master clock, correct to within half a second.

OXFORD, ENGLAND

Seismologic Station[1], inaugurated in October, 1919.
Prof. Herbert Hall Turner, Director.
Seismological Committee, Brit. Ass. Adv. Sci.

Postal address: Seismologic Station, Oxford University Observatory, Oxford, England.

$\varphi = 51°45'34.2''$ N., $\lambda = 1°15'06''$ W., h = ca. 64 m.

Lithologic foundation: not stated.

Equipment: Milne-Shaw seismograph, E comp.
Constants: V = 260, $T_0 = 12$ sec.

Time service: time comparisons made by radiotelegraphic signals, correct within ±1 sec.

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[1] This station replaces that so long maintained on the Isle of Wight by the late John Milne.

*PADUA, ITALY

Instituto Fisico della R. Università.

Postal address: Padova, Italia.

$\varphi = 45°24'02.5''$ N., $\lambda = 11°52'18''$ E., h = ca. 20 m.

Lithologic foundation: alluvium (Recent and Quaternary).

Equipment: Vicentini microseismograph, mass 400 kg., two horizontal comp.
Constants: V = 90 to 110, $T_0 = 6.7$ sec., special aperiodic damping.
Vicentini microseismograph, mass 100 kg.
Constants: two horizontal comp., V = 125 to 140, $T_0 = 2.3$ sec.
one vertical " V = 145 " 165, $T_0 = 1.2$ "

Time service: time comparisons are obtained by electric signals from the neighboring Astronomical Observatory.

*PAISLEY, SCOTLAND

Seismologic Station, inaugurated in 1902.
David Crilley, Esq., Director.
The Coats Observatory.

Postal address: Seismologic Station, The Coats Observatory, Paisley, Scotland.

$\varphi = 55^\circ 50' 43.8''$ N., $\lambda = 4^\circ 25' 49.5''$ W., h = ca. 32 m.

Lithologic foundation: boulder clay on limestone or sandstone.

Equipment: Milne seismograph.

*PAMPLEMOUSSES, MAURITIUS

Seismologic Station, inaugurated in September, 1898.
Royal Alfred Observatory.

Postal address: Seismologic Station, Royal Alfred Observatory, Pamplemousses, Mauritius.

$\varphi = 20^\circ 05' 39''$ S., $\lambda = 57^\circ 33' 09''$ E., h = ca. 51 m.

Lithologic foundation: heavy concrete pier on soil 1 to 4 m. thick resting on solid basalt.

Equipment: Milne seismograph, two horizontal comp.

Time service: time observations are made daily (presumably by meridian transit).

PARC SAINT MAUR (PARIS), FRANCE

Observatoire du Parc Saint Maur, seismologic service inaugurated in 1908.
M. Ch. Dufour, Meteorologist, in charge of Observatory.
M. Eblé, in charge of seismologic work.
Bureau Centrale Meteorologique de France.

Postal address: Observatoire du Parc Saint Maur, Seine, France.

$\varphi = 48^\circ 48.6'$ N., $\lambda = 2^\circ 10.9'$ E., h = 50 m.

Lithologic foundation: limestone of the Paris basin.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E. Bosch-Mainka horizontal pendulum, mass 400 kg., two comp. N and E. Galitzin seismograph, photo-galvanometric registration, three comp.

Constants:		V	T_0	ϵ	r
Wiechert,	N,	ca. 225	ca. 11.1 sec.	ca. 5.0	ca. 0.7
"	E,	" 240	" 11.2 "	" 4.7	" 0.8
Mainka,	N,	" 160	" 9.2 "	" 5.5	" 0.7
"	E,	" 150	" 8.5 "	" 3.5	" 1.2

Time service: time is kept and minute time marks are made electromagnetically by a compensated contact clock; time comparisons are made daily by radiotelegraphic signals from the Eiffel tower, accurate to 0.5 sec.

PAVIA, ITALY

R. Osservatorio Geodinamico, inaugurated in 1891.

Prof. Dr. Pericle Gomba, Director.

Ufficio Centrale di Meteorologia e Geodinamica, Roma.

Postal address: R. Osservatorio Geodinamico, Pavia, Italia.

$\varphi = 45°11'06''$ N., $\lambda = 9°10'25''$ E., h = 77 m.

Lithologic foundation:

Equipment: Vicentini seismograph. Agamennone seismograph.

Time service: time comparisons by telephone from the Astronomical Observatory at Milan, approx. accuracy 1 sec.

PERTH, AUSTRALIA

The Perth Observatory.

H. B. Curlewis, The Government Astronomer for Western Australia, Director.

The Government of Western Australia.

Postal address: The Observatory, Perth, Western Australia.

$\varphi = 31°57'08.6''$ S., $\lambda = 115°50'26.1''$ E., h = ca. 60 m.

Lithologic foundation: solid sand with limestone beneath.

Equipment: Milne seismograph, N comp.
Constants: 1 mm. displacement = 0.62″, 18 inches = 1 hour.

Time service: light eclipsed once each hour by an electromagnetic shutter operated by the Mean Time clock of the Observatory; also, light eclipsed every five minutes by an electromagnetic shutter operated by a secondary clock having a uniform rate: time marks are correct to about 0.2 min.

*PIC DU MIDI (BAGNÈRES DE BIGORRE), HAUTES PYRENEES, FRANCE

Seismologic Station at Bagnères, a sub-station of Observatoire du Pic du Midi, Université de Toulouse.

Postal address: Observatoire du Pic du Midi, Bagnères de Bigorre, Hautes Pyrenees, France.

(The latitude and longitude of the station at Bagnères is not available.) h = 547 m.

$\varphi = 42°56'17''$ N., $\lambda = 0°08'30''$ E., h = 2,859 m. (of Observatory).

Lithologic foundation: at Bagnères, morainic detritus and alluvium: (at the Observatory, crystalline rock).

Equipment: Marchand recording seismograph. Marchand seismoscope.

PILAR (CÓRDOBA), ARGENTINA

Observatorio Magnético, seismologic service inaugurated in January, 1905.

Observer subject to change.

Oficina Meteorológica Argentina.

Postal address: Jefe de la Oficina Meteorológica Argentina, Paseo Colon 974, Buenos Aires, Argentina.

$\varphi = 31°40'13''$ S., $\lambda = 63°53'$ W., h = 330 m.

Lithologic foundation: alluvial.

Equipment: Milne seismograph, two comp. N and E.
Constants: $T_0 = 17$ sec.; N, 1 mm. displacement = 0.48″,
E, 1 " " = 0.41″.

Time service: Time marks made every two hours. Chronometer checked daily by telephone with time of Astronomical Observatory. Time is accurate, and seismograms are read to 0.1 minute.

*PJATIGORSK, RUSSIA

Seismologic Station, a station of the second class of the Russian service.

Equipment: Zöllner horizontal pendulums.

PLAUEN-VOGTLAND, GERMANY

Erdbeben-Station, inaugurated August 29, 1905.

Prof. E. Weise, Director.

Hauptstation der Geologischen Landesuntersuchung von Sachsen in Leipzig.

Postal address: Erdbeben-Station, Plauen-Vogtland, Sachsen, Deutschland. Neundorfer Str. 55.

$\varphi = 50°29.9'$ N., $\lambda = 12°09.2'$ E., h = 380 m.

Lithologic foundation: brick pier, free from the floor, on breccia (Upper Devonian).

Equipment: Wiechert inverted pendulum, N comp.
Constants: L = 12.25 m., V = 116, $T_0 = 7$ sec., $\epsilon = 1.2$, r = 2.5.

Time service: time is kept and time marks are made electromagnetically by a Göttingen pendulum clock compared twice a week by means of the telegraphic time service of the Berlin Astronomical Observatory.

POINT LOMA, CALIFORNIA

Co-öperative Meteorological Station of the U. S. Weather Bureau, seismologic service inaugurated in 1906.
Fred J. Dick, Co-operative Observer.
Theosophical University.

Postal address: The Meteorological Station, Theosophical University, Point Loma, California.

$\varphi = 32°43'03''$ N., $\lambda = 117°15'10''$ W., h = 91.4 m.

Lithologic foundation: aeolian hard pan, on sandstone (Jurassic).

Equipment: "Two-horizontal-component astatic arrangement, on lines of a suggestion by C. D. West. (See Milne: *Earthquakes*.) No magnification. Longitudinally each of the heavy weights has no period—each being astatic in that direction. The transverse pendulum-action produces no record on the smoked glass. In addition there is an arrangement for recording any vertical movement of the ground upon the same smoked glass plate."

Time service: approximate to half minute only.

POLA, ITALY

Ufficio Idrografico della R. Marina (Sezione Geofisica), seismologic service inaugurated in April, 1914.
Captain Augusto Spagnoli, Director.

Postal address: Ufficio Idrografico della R. Marina (Sezione Geofisica), Pola, Italia.

$\varphi = 44°51'49''$ N., $\lambda = 13°50'46''$ E., h = 32 m.

Lithologic foundation: limestone.

Equipment: Wiechert astatic pendulum, mass 1,000 kg., two comp. Constants:

	V	T_0	ϵ	r/T_0^2
N,	228	10.8	1.96	0.0161
E,	230	11.0	2.22	0.0157

Time service: time is determined to tenths of seconds.

*PONTA DELGADA, AZORES

Serviçao Meteorologico dos Açores.

Postal address: Ponta Delgada, San Miguel, Açores.

$\varphi = 37°44'$ N., $\lambda = 25°41'$ W., h = 16 m.

Lithologic foundation: basaltic rock.

Equipment: Milne seismograph, E comp.

PORT-AU-PRINCE, HAITI

Observatoire metéorologique, seismologic service inaugurated in May, 1912.
Prof. J. Scherer, Director.
College St. Martial.

Postal address: Observatoire Metéorologique, Port-au-Prince, Haiti.

$\varphi = 18°33'20''$ N., $\lambda = 72°20'15''$ W., h = ca. 25.9 m.

Lithologic foundation: calcareous tufa, beds of shingle, argillaceous marl.

Equipment: Bosch-Omori seismograph, two comp. NE and NW.
Constants: $V = 40$, $T_0 = 11$ sec., no damping, 13 to 14 mm. = 1 minute.

Time service: time comparisons are made by radiotelegraphic signals, and by means of meridian circle observations.

*PORT OF SPAIN, TRINIDAD

Seismologic Station, inaugurated about 1900.
W. G. Freeman, B.Sc., Director.
St. Clair Experiment Station of the Botanical Gardens.

Postal address: Seismologic Station, St. Clair Experiment Station, Port of Spain, Trinidad, W. Indies.

$\varphi = 10°38'39''$ N., $\lambda = 61°30'39''$ W., h = 20.5 m.

Lithologic foundation: sands and clays.

Equipment: Milne seismograph, E comp.

Time service: based on daily astronomical observations.

*PORTICI, NAPLES, ITALY

Osservatorio Meteorologico e Geodinamico.

Postal address: Portici, presso Napoli, Italia.

$\varphi = 40°48'$ N., $\lambda = 14°20'$ E., h = ca. 80 m.

Equipment: Agamennone seismometrograph, mass 120 kg., two horizontal comp., registering with ink.
Constants: $V = 14$, $T_0 = 5.1$ s.

Time service: time is checked by the midday cannon at Naples.

PORTO ALEGRE, RIO GRANDE DO SUL, BRAZIL

At the Engineering School there is a Wiechert seismograph, mass 120 kg., not yet in use.

PORTO D'ISCHIA (NAPLES), ITALY

R. Osservatorio Meteorologico e Geodinamico—Porto d'Ischia, seismologic service inaugurated August 17, 1885.
Dr. Giulio Grablovitz, Director.
R. Ufficio Centrale di Meteorologia e Geodinamica in Roma,
Ministero por l'Agricoltura.

Postal address: R. Osservatorio Geodinamico, oppure Via Terme 165, Ischia (Napoli), Italia.

$\varphi = 40°44'26.7''$ N., $\lambda = 13°56'35.1''$ E., h = 36.72 m.

Lithologic foundation: ash and tufaceous and trachytic material over trachyte.

Equipment: horizontal pendulum, local model, mass 12 kg.
"Vasca sismica."

Time service: time is kept by high grade clocks and chronometers; time comparisons are made by astronomical observations.

*PORTO MAURIZIO, ITALY

Osservatorio Meteorico e Sismico, seismologic service inaugurated about 1910 (?).

Postal address: Osservatorio Meteorico e Sismico, Porto Maurizio, Italia.

$\varphi = 43°53'$ N., $\lambda = 8°03'$ E., h = ca. 50 m. (ca. 24 cm. ?).

Equipment: Agamennone seismometrograph[1], mass 200 kg., two horizontal comp. registering with ink.
Constants: $V = 12$, $T_o = 2.5$ sec.
Several seismoscopes.

Time service: time is determined by sextant observations.

[1] Transferred to this station from Turin about 1910.

PORTO RICO, see VIEQUES

*POTSDAM, GERMANY

Seismic Observatory, inaugurated in 1901.
Kgl. Preussisches Geodätisches Institut.

Postal address: Seismic Observatory, Potsdam, Deutschland.

$\varphi = 52°22'51''$ N., $\lambda = 13°03'59''$ E., h = ca. 90 m.

Lithologic foundation: sand.

Equipment: modified Rebeur-Paschwitz horizontal pendulum, mass 70 grams, two horizontal comp.
Constants: $V=36$, $T_0=18$ sec.
Wiechert inverted pendulum, mass 1,000 kg., two comp.
Constants: $V=133$, $T_0=14$ sec.
A vertical-motion seismograph.
Rebeur-Hecker horizontal pendulums used for experiments on the rigidity of the earth.

PUEBLA, MEXICO

Estación Seismológica de Puebla, a station of the second order.
Francisco de P. Tenorio, Jefe de la Estación.
Servicio Seismológico Nacional de México,
Instituto Geológico Nacional.

Postal address: Instituto Geológico Nacional, 6a del Cipres núm. 176, México, D. F., República Mexicana.

$\varphi=19°03'$ N., $\lambda=98°12'$ W., $h=2{,}132$ m.

Lithologic foundation: basalt.

Equipment: Wiechert seismograph, third-order type, mass 10 kg., two comp. N and E. Milne seismograph, three comp.

Time service: time comparisons by telegraphic signals from Tacubaya.

*PULKOVA, near PETROGRAD, RUSSIA

Central Seismologic Station, the chief station of the Russian service.

Postal address: Central Seismologic Station, Pulkova, near Petrograd, Russia.

$\varphi=59°46'$ N., $\lambda=30°19'$ E.,

Lithologic foundation: (piers are in a specially constructed building entirely underground).

Equipment: Galitzin aperiodic seismometer, galvanometric-photographic registration, three comp.: two complete sets, one group adjusted to record stronger, another group adjusted to record weaker teleseismic motion.
Galitzin seismograph, mech. registr., three comp.

Time service: of the Astronomical Observatory.

*PUNTA ARENAS, CHILE

Seismologic Station.

Postal address: Servicio Sismolójico de Chile, Santiago, Chile.

$\varphi = 53°10'$ S., $\lambda = 70°54'$ W.

Lithologic foundation: sand.

Equipment: Wiechert inverted pendulum, mass 180 kg., two comp. N and E.

Time service: time is kept and minute time marks are made by a contact clock compared weekly by telegraphic signals from the central station at Santiago.

PUY DE DÔME, see CLERMONT-FERRAND

QUARTO CASTELLO, see FLORENCE

*QUENAST, BELGIUM

Seismologic Station, inaugurated in 1899.
Société des Carrières de Quenast.

Postal address: Seismologic Station, Quenast, Belgium.

$\varphi = 50°39'45''$ N., $\lambda = 4°10'50''$ E., $h = 30$ m.

Lithologic foundation: compact porphyry.

Equipment: Rebeur-Ehlert triple horizontal pendulum.

*QUITO, ECUADOR

Observatorio Astronomico y Meteorologico.

Postal address: Quito, Ecuador.

$\varphi = 0°13'51''$ S., $\lambda = 78°32'30''$ W., $h = 2{,}908$ m.

Equipment: Bosch seismograph.

*RENO, NEVADA

Seismologic Station, inaugurated in 1911.
Prof. J. Claude Jones, in charge.
Department of Geology, University of Nevada.

Postal address: Seismologic Station, University of Nevada, Reno, Nevada.

$\varphi =$ ca. $39°30'$ N., $\lambda =$ ca. $119°50'$ W.

Equipment: Ewing Duplex seismograph, $V = 4$.

*REYKJAVIK, ICELAND

International Station, seismologic service inaugurated in 1909; attached to the Danish School of Navigation of Reykjavik.

Postal address: Seismologic Station, Danish School of Navigation, Reykjavik, Iceland.

$\varphi = 64°08'32''$ N., $\lambda = 21°55'45''$ W.

Lithologic foundation: solid rock.

Equipment: Mainka horizontal pendulum, one comp.

RICHMOND, SURREY, ENGLAND

Kew Observatory, seismologic service inaugurated in March, 1898.
Charles Chree, Assistant Director of Geophysics.
Meteorological Office, Department of Civil Aviation, Air Ministry.

Postal address: Kew Observatory, Richmond, Surrey, England.

$\varphi = 51°28'06''$ N., $\lambda = 0°18'47''$ W., h = 5 m.

Lithologic foundation: river gravel resting on chalk.

Equipment: Milne seismograph (old pattern), E comp.
Constants: T_0 = ca. 18 sec., 1 mm. displacement = 0.5″, 1 mm. = 1 min.

Time service: time comparisons are made by signal from Greenwich with an accuracy of ca. 0.25 sec. Seismic times never given to nearer than 0.1 minute, usually to nearest minute.

RIO DE JANEIRO, BRAZIL

Observatorio Nacional[1], seismologic service inaugurated in 1906.
Prof. Dr. Henrique Morize, Director of the Observatory.
Alix Lemos, Assistant in charge of Geophysics.
Ministerio da Agricultura, Industria e Commercio.

Postal address: Observatorio Nacional, Rio de Janeiro, Brazil.

$\varphi = 22°54'23.6''$ N., $\lambda = 43°10'21.15''$ W., h = 60 m.

Lithologic foundation: slate or shale.

Equipment: Mainka bifilar horizontal pendulum, mass 400 kg. Mainka bifilar horizontal pendulum, mass 120 kg. Wiechert vertical-motion seismograph. A Milne-Shaw seismograph is to be installed.

Time service: time is kept accurately to 0.1 sec.; time determinations are made by meridian transit observations; seismometric readings are accurate to ca. 1 sec.

[1] Observatory recently removed to new quarters; re-installation not complete.

RIO TINTO MINES, SPAIN

Postal address: Rio Tinto Mines, España.

$\varphi = 37°46'$ N., $\lambda = 6°38'$ W., h = 427 m.

Lithologic foundation: slate (Lower Carboniferous).

Equipment: Milne seismograph, one comp. N.
Constants: $T_0 = 18$ sec., 1 mm. displacement = 0.5″ approx.

Time service: variations of five minutes not unusual.

ROCCA DI PAPA (ROME), ITALY

R. Osservatorio Geodinamico di Rocca di Papa, seismologic service inaugurated in 1889.
Prof. Dr. Cav. Uff. Giovanni Agamennone, Director.
R. Ufficio Centrale di Meteorologia e Geodinamica, Roma.

Postal address: R. Osservatorio Geodinamico di Rocca di Papa, presso Roma, Italia.

$\varphi = 41°45.5'$ N., $\lambda = 12°43'$ E., h = 760 m.

Lithologic foundation: lava.

Equipment: Agamennone microseismograph, mass 1,800 kg., two horizontal comp.
Constants: V = ca. 400, $T_0 = 2.3$ sec., 70 cm. = 1 hour.
Agamennone horizontal pendulum, mass 3,000 kg., N comp.
Constants: V = 110, $T_0 = 15$ sec., 96 cm. = 1 hour.
Agamennone universal microseismometrograph, three comp.
Constants: N and E comp., Mass = 400 kg., V = 100, $T_0 = 8$ sec.; {96 cm.
Z " " = 250 " V = 100, $T_0 = 4$ " = 1 hr.
Each of the masses can be increased up to 1,000 kg.

Agamennone seismometrograph, mass 200 kg., two comp.
Constants: V = 14, $T_0 = 4.3$ sec., 36 cm. = 1 hour, except that for 90 sec. following the beginning of an earthquake the cylinder speeds up and runs at the rate of 20 m. per hour, and then runs at its usual rate.
Brassart seismometrograph, three comp., with sporadic registration following the beginning of an earthquake.

Constants:	Mass	V	T_0
N,	10 kg.	10	4.3 sec.
E,	10 "	10	4.3 "
Z,		10	2.0 "

Runs about 60 cm. at the rate of 30 m. per hour.

Agamennone macroseismograph, three comp., registers after beginning of a shock.
Constants: N and E, Mass 2 kg. V = 1 to 2, $T_0 = 4$ sec.;
Z V = 1 " 2, $T_0 = 2$ "

Various seismoscopes, three groups of sensitiveness.
All the seismographs are provided with appropriate damping.

Time service: minute, half-hour, and hour time marks made electromagnetically by a contact chronometer (marine type) checked by telephone with R. Specola Astronomica di Roma at the Collegio Romano: accuracy of about 1 sec.

ROME, ITALY

Stazione Sismica Sperimentale al Collegio Romano, inaugurated in August, 1909.
Prof. Commendatore Luigi Palazzo, Director.
Ministero dell' Agricoltura.

Postal address: R. Ufficio Centrale di Meteorologia e Geodinamica, Via Caravita N. 7, Roma, Italia.

$\varphi = 41°54'$ N., $\lambda = 12°29'$ E., h = ca. 30 m.

Lithologic foundation: (Quaternary).

Equipment: Agamennone horizontal pendulum, mass 50 kg.
Constants: $V = 50$, $T_0 = 8$ sec., ca. 1.6 m. = 1 hour.

Time service: time is kept and hour and minute time marks are made electromagnetically by a contact marine chronometer compared daily by signals from the R. Osservatorio Astronomico del Collegio Romano; accuracy of seismometric readings about 2 sec.

ROQUETAS, see TORTOSA

SAGA, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1915.
K. Miyazima, Director.
Supported by the local prefecture.

Postal address: Saga Meteorological Observatory, Saga, Japan.

$\varphi = 33°12'$ N., $\lambda = 130°18'$ E., h = 11.5 m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E. $V = 20$.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

ST. BONIFACE, MANITOBA, CANADA

L'Observatoire Sismique, inaugurated January 21, 1910.

Prof. Albert Buron, S.J., in charge.
College de St. Boniface.

Postal address: Seismic Observatory, College de St. Boniface, Manitoba, Canada.

$\varphi = 49°53'31''$ N., $\lambda = 97°06'39''$ W., h = 230 m.

Lithologic foundation: 18 m. of shale over rock (Ordovician).

Equipment: Wiechert inverted pendulum, mass 80 kg. V = 80.

Time service: time is kept and hour and minute time marks are made electromagnetically by an ordinary contact clock of good rate compared with the time service of the C. P. Ry.

*ISLAND OF ST. HELENA

Seismologic Station, inaugurated in February, 1911.
Eastern, Eastern Extension and Pacific Telegraph Co.

Postal address: Seismologic Station, Island of St. Helena.

$\varphi = 15°55'$ S., $\lambda = 5°44'$ W.

Equipment: Milne seismograph, E comp.

ST. LOUIS, MISSOURI

Earthquake Station, inaugurated January 1, 1910.
Prof. J. B. Goesse, Director.
St. Louis University.

Postal address: Earthquake Station, St. Louis University, Grand and Lindell Boulevard, St. Louis, Missouri.

$\varphi = 38°38'17''$ N., $\lambda = 90°13'58.3''$ W., h = 160.36 m.

Lithologic foundation: ca. 3 m. clay over limestone (Mississippi).

Equipment: Wiechert inverted pendulum, mass 80 kg., two comp. N and E., $T_0 = 7$ sec.

Time service: time kept and marked electromagnetically by a contact clock compared by means of radiotelegraphic signals.

SAKAI, JAPAN

Meteorological Observatory, seismologic service inaugurated in March, 1916.
K. Takakuwa, Director.
Supported by the Tottori prefecture.

Postal address: Sakai Meteorological Observatory, Sakai, Tottori-ken, Japan.

$\varphi = 35°33'$ N., $\lambda = 133°14'$ E., h = 2.1 m.

Lithologic foundation: alluvium.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V=20$, $T_0=4$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*SALÒ, near BRESCIA, ITALY

R. Osservatorio Geodinamico.

Postal address: Salò, presso Brescia, Italia.

$\varphi=45°36'27''$ N., $\lambda=10°30'45''$ E., h=ca. 80 m.

Equipment: Agamennone seismometrograph, mass 220 kg., two horizontal comp. registering with ink.
Constants: $V=10$, $T_0=7.8$ sec., 33 cm. = 1 hour.
Agamennone seismoscope.

Time service: time is checked with the time of the telegraph office.

*SALT LAKE CITY, UTAH

Seismologic Station.
Prof. Fred J. Pack, in charge.
University of Utah.

Postal address: Seismologic Station, University of Utah, Salt Lake City, Utah.

$\varphi=$ ca. $40°46'$ N., $\lambda=$ ca. $111°50'$ W.,

Equipment: Bosch-Omori horizontal pendulum, two comp.

Note: these instruments are installed only a short distance from the great fault at the western base of the Wasatch mountains.

SAN FERNANDO (CADIZ), SPAIN

Seismologic Station, inaugurated in 1898.
Contralmirante Tomás de Azcárate, Director.
Observatorio de Marina de San Fernando.

Postal address: Observatorio de Marina, San Fernando, España.

$\varphi=36°27'42''$ N., $\lambda=6°12'19.5''$ W., h=28.5 m.

Lithologic foundation: calcareous rock.

Equipment: and constants:		Mass	V	T_0	r/T_0^2
Milne seismograph,	N comp.	1 kg.	7	20 sec.	
" "	E "	1 "	7	17 "	

Equipment: and constants:		Mass	V	T_0	r/T_0^2
"Observatory" seismograph,	E comp.	700 kg.	280	2.1 sec.	0.067
"Observatory" bifilar horiz.	E "	60 "	13	24 "	0.001
Ewing seismograph,					

Time service: of the Observatorio de Marina, not minutely specified.

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[1] An ordinary vertical, or simple, pendulum.

SAN JOSÉ, CALIFORNIA

Seismologic Station, inaugurated about 1888.

Louis S. Kroeck, Director.
College of the Pacific.

Postal address: Seismologic Station, College of the Pacific, San Jose, California.

$\varphi = 37^\circ 20' 38.2''$ N., $\lambda = 121^\circ 55' 03''$ W., h = ca. 9 m.

Lithologic foundation: sedimentary rock.

Equipment: Ewing seismograph.

Time service: not specified.

*SAN LUCA, BOLOGNA, ITALY

Osservatorio Meteorologico e Sismico "Malvasia."

Postal address: San Luca Bologna, Italia.

$\varphi = 44^\circ 29'$ N., $\lambda = 11^\circ 18'$ E., h = ca. 290 m.

Equipment: Stiattesi horizontal pendulums, mass 500 kg., two comp. Constants: $V = 80$, $T_0 = 4.6$ sec., 180 cm. = 1 hour.

Time service: time comparisons are furnished by the Astronomical Observatory of Bologna.

*SAN SALVADOR, CENTRAL AMERICA

Fisica Modela, seismologic service inaugurated in 1916.

Señor Sanz. Gr. Barbarena, Director.

Postal address: Seismologic Station, Fisica Modela, San Salvador, C. A.

$\varphi = 13^\circ 43' 44''$ N., $\lambda = 89^\circ 14' 30''$ W.,

Equipment: Vicentini microseismographs. Bosch-Omori horizontal pendulums. Agamennone macroseismometrograph.

SANTA CLARA, CALIFORNIA

Seismologic Station, inaugurated in 1909.

Rev. Jerome S. Ricard, S.J., Director.
Observatory, University of Santa Clara.

Postal address: Observatory, University of Santa Clara, Santa Clara, California.

$\varphi = 37°20'45''$ N., $\lambda = 123°15'00''$ W., h = ca. 28 m.

Lithologic foundation: adobe, hardpan, sand, gravel; old sea bottom.

Equipment: Wiechert inverted pendulum, two horiz. comp.
" vertical-motion seismograph, Z comp.
Mass = 80 kg., $\epsilon = 5$.

Time service: time is kept and hour and minute time marks are made electromagnetically by a standard contact clock compared daily by radiotelegraphic and telegraphic signals from the Mare Island Observatory; accurate within 1 to 2 sec.

SANTIAGO, CHILE

Central Seismologic Station, inaugurated June 9, 1908.
Comte F. de Montessus de Ballore, Director.
Servicio Sismolójico de Chile.

Postal address: Servicio Sismolójico de Chile, Santiago, Chile.

(The Cerro Santa Lucia Park Observatory is situated 4 km. east of the old Santiago Astronomical Observatory.)

$\varphi = 33°26'42''$ S., $\lambda = 70°40'$ W., h = 580 m.

Lithologic foundation: trachytic rock.

Equipment: Wiechert inverted pendulum, mass 180 kg., two comp. N and E., with damping.
Wiechert vertical-motion seismograph, mass 100 kg., Z comp., with damping.
Bosch-Omori horizontal pendulum, mass 100 kg., two comp. NW and NE, with air damping. $T_0 = 36$ sec.
Stiattesi horizontal pendulum, mass 1,000 kg., two comp. N and E.
De Montessus cardanic pendulum, mass 40 kg., one comp.

Time service: time is kept and minute time marks are made by a contact clock compared daily by a gun-fire signal with the time service of Lo Espejo Astronomical Observatory.

SAPPORO, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1910.
S. Takayura, Director.

Supported by the Hokkaido government.

Postal address: Sapporo Meteorological Observatory, Sapporo, Japan.

$\varphi = 43°04'$ N., $\lambda = 141°21'$ E., h = 15.1 m.

Lithologic foundation: soft sandy soil.

Equipment: Omori horizontal pendulum tromometer, E comp.
Constants: V = 30, $T_o = 19.2$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*SARAJEVO, JUGOSLAVIA

Meteorological and Seismological Observatory, seismologic service inaugurated in 1905.

Postal address: Seismological Observatory, Sarajevo, Jugoslavia.

$\varphi = 43°52'08''$ N., $\lambda = 18°25'39''$ E., h = 673 m.

Lithologic foundation: marls and sandstones (Tertiary).

Equipment: Vicentini microseismograph, mass 100 kg., two horizontal comp., 90 cm. = 1 hour.
Wiechert inverted pendulum, mass 200 kg., two comp., 60 cm. = 1 hour.

SASKATOON, SASKATCHEWAN, CANADA

Seismological Station, inaugurated in April, 1915.
Prof. Alexander G. McGougan, Director.
Department of Physics, University of Saskatchewan.

Postal address: Seismologic Station, University of Saskatchewan, Saskatoon, Sask., Canada.

$\varphi = 52°08'$ N., $\lambda = 106°30'$ W., h = ca. 515 m.

Lithologic foundation: clay and sand.

Equipment: Mainka bifilar horizontal pendulum, mass 139.3 kg., two comp. N and E.
Constants: N, $T_o = 9.1$ sec., $\epsilon = 5$; E, $T_o = 9.3$ sec., $\epsilon = 5$.

Time service: time is kept and hour and minute time marks are made electromagnetically by a Bosch contact clock compared monthly by telegraphic signal; probably reliable within 2 sec.

*SEATTLE, WASHINGTON

Seismologic Station, inaugurated in 1906.
Prof. E. J. Saunders, in charge.
Department of Geology, University of Washington.

Postal address: Seismologic Station, University of Washington, Seattle, Washington.

$\varphi=47°39'06''$ N., $\lambda=122°18'30''$ W., h=ca. 50 m.

Lithologic foundation: glacial drift.

Equipment: Bosch-Omori seismograph, mass 50 kg.

*ŠEMAKHA, CAUCASUS, RUSSIA

Seismologic Station.

$\varphi=40°38'$ N., $\lambda=48°38'$ E.

Equipment: Bosch-Omori horizontal pendulum, two horizontal comp.

SHIONOMISAKI, JAPAN

Meteorological Observatory, seismologic service inaugurated in December, 1912.
K. Yamasawa, Director.
Supported by the Central Meteorological Observatory.

Postal address: Shionomisaki Meteorological Observatory, Shionomisaki, Wakagawa-ken, Japan.

$\varphi=33°27'$ N., $\lambda=135°46'$ E., h=72.9 m.

Lithologic foundation: rock.

Equipment: Omori horizontal pendulum tromometer, N comp.
Constants: $V=120$, $T_0=12.5$ sec.
Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V=60$, $T_0=4$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

SIENA, ITALY

Osservatorio Geodinamico di Siena, seismologic service inaugurated June 1, 1918 (1908?).
P. L. Atto Maccioni, Director.
R. Università.

Postal address: Osservatorio Geodinamico di Siena, R. Università, Italia.

$\varphi=43°19'$ N., $\lambda=11°20.5'$ E., h=348 m.

Lithologic foundation: calcareous tuff.

Equipment: Vicentini microseismograph, mass 200 kg., two comp.
Constants: $V=100$, $T_0=3.5$ sec., 90 cm. = 1 hour.
Horizontal pendulum tromograph, mass ca. 60 kg., two comp. N and E.
Constants: $V=12$, $T_0=12$ sec.

Vertical-motion seismograph, mass 15 kg., Z comp.
Constants: $V=10$, $T_0=1$.
Electric and mechanical seismoscopes and a "source indicator," some of which are fitted to register "occasionally."

Time service: time is kept and minute time marks are made by a contact pendulum clock checked every eight days by radiotelegraphic signals.

*SIENA, ITALY

Osservatorio Sismico dell' Osservanza[1], inaugurated in 1908.

Postal address: Siena, Toscana, Italia.

$\varphi=43°19'$ N., $\lambda=11°20.5'$ E., h = ca. 330 m.

Equipment: Agamennone seismometrograph, mass 200 kg., two comp.
Constants: $V=10$, $T_0=3$ sec., 60 cm. = 1 hour.
Stiattesi horizontal pendulum, mass 60 kg.
Constants: $V=6$, $T_0=18$ sec.
Vicentini microseismograph, mass 500 kg., two horizontal comp.
" " Z comp.
Agamennone seismoscope.
Cecchi alarm.

Time service: time is determined by meridian passage of the sun, but the error may amount to one minute.

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[1] This station took over the instruments at the observatory at Giaccherino, which was discontinued in 1907.

SIMLA, INDIA

Seismologic Station, inaugurated in June, 1905. Removed to present site October 1, 1917.
Dr. Gilbert Thomas Walker, Director General of Observatories.
India Meteorological Department.

Postal address: Meteorological Office, Simla, India.

$\varphi=31°06'$ N., $\lambda=77°11'$ E., h = 2200 m.

Lithologic foundation: rock (schist and quartzite underlaid by Carboniferous strata).

Equipment: Omori-Ewing horizontal pendulum, mass 50 kg., two comp. N and E.
Constants: $V=14$, $T_0=45$ sec.

Time service: time comparisons by radiotelegraphic signals from Calcutta, ordinarily correct to a second.

Publication: Data published in India Monthly Weather Review; also sent to the Seismological Committee of the Brit. Ass. Adv. Sci.

SITKA, ALASKA

Sitka Magnetic Observatory, seismologic service inaugurated in April, 1904.
Magnetic Observer, in charge, Franklin P. Ulrich, present incumbent.
U. S. Coast and Geodetic Survey.

Postal address: Magnetic Observatory, U. S. C. and G. S., Sitka, Alaska, or U. S. Coast and Geodetic Survey, Washington, D. C.

$\varphi = 57°03'$ N., $\lambda = 135°20.1'$ E., $h = 15.2$ m.

Lithologic foundation: concrete piers, through peaty soil, to granitic rock.

Equipment: Bosch-Omori horizontal pendulum, mass 10 kg., two comp. N and E., mech. registr. on smoked paper.
Constants: N, $V = 10$, $T_0 = 16$ sec.; E, $V = 10$, $T_0 = 18$ sec.

Time service: two box chronometers; corrections and rates determined by means of telegraphic time signals. The time of stopping and starting the record is noted daily by one of the chronometers. The seismograph clock, which makes a mark each minute on the smoked paper (one minute = 15 mm.), is not of a high grade, but when in good adjustment has a fairly uniform rate, so that the time of the minute marks in the middle of a sheet are uncertain by not more than 10 sec., and correspondingly less near the beginning or end.

SOFIA, BULGARIA

Seismologic Station, inaugurated April 16, 1905.
Le Directeur de l'Institut Météorologique de Bulgarie.

Postal address: Institut Météorologique de Bulgarie, Sofia, Bulgarie.

$\varphi = 42°41'40''$ N., $\lambda = 23°19'39''$ E., $h = 540$ m.

Lithologic foundation: thin diluvial gravel.

Equipment: Bosch-Omori horizontal pendulum, mass 10 kg., two comp. N and E.

Horizontal pendulum, mass 25 kg., one comp. N 60° W, $T_0 = 13.4$ sec.

Time service: time is determined by the chronodeik of Palisa, with an accuracy of ca. 5 sec.

SOUTH YARRA, VICTORIA, AUSTRALIA

Melbourne Observatory, seismologic service inaugurated in 1900.
Joseph Mason Baldwin, Government Astronomer of Victoria.

Government of Victoria.

Postal address: Melbourne Observatory, South Yarra, Victoria, Australia.

$\varphi = 37^\circ 50'$ S., $\lambda = 144^\circ 58'$ E., h = ca. 25.9 m.

Lithologic foundation: stratified rock (Pliocene) on older rock.

Equipment: Milne seismograph, early form, E comp.
Constants: $T_0 = 18$ sec., 1 mm. displacement = 0.5″, 3 mm. = 1 minute.

Time service: time is kept, and marked by eclipse once each hour, by the Observatory clocks; accurate within 2 seconds.

SPOKANE, WASHINGTON

Seismologic Station, inaugurated in 1909.
A. M. Jung, Seismologic Observer, in charge.
Gonzaga University.

Postal address: Seismologic Station, Gonzaga University, Spokane Washington.

$\varphi = 47^\circ 40' 04''$ N., $\lambda = 117^\circ 25' 15''$ W., h = 584.15 m.

Lithologic foundation: concrete base on gravel and sand, lake beds.

Equipment: and constants:	V	T_0	ϵ
Wiechert inverted pendulum, mass 80 kg., N comp.,	80	5.9	8
E "	80	5.1	8

Time service: time is kept and hour and minute time marks are made electromagnetically by a Göttingen clock compared with a Western Union clock regulated by the U. S. Naval Observatory; accuracy ca. 1 sec.

SPRING HILL (MOBILE), ALABAMA

Seismic Observatory, inaugurated in October, 1910.
Prof. Rev. Cyril Ruhlmann, S.J., in charge.
Spring Hill College.

Postal address: Seismic Observatory, Spring Hill College, Spring Hill, Mobile Co., Alabama.

$\varphi = 30^\circ 41' 44''$ N., $\lambda = 88^\circ 08' 46''$ W., h = 60 m.

Lithologic foundation: alluvial.

Equipment: Wiechert inverted pendulum, mass 80 kg., two comp.
Constants: undetermined.

Time service: time is kept and minute time marks are made electromagnetically by a contact clock (Wiechert) equipped with a compensating pendulum, compared daily by radiotelegraphic signals from Arlington.

STARÁ ĎALA (formerly ÓGYALLA), CZECHO-SLOVAKIA

Seismologic Station, inaugurated in 1900.
Meteorological and Magnetic Observatory.

Postal address: Seismologic Station, Meteorological and Magnetic Observatory, Stará Ďala, Czecho-Slowakia.

$\varphi = 47°52'$ N., $\lambda = 18°12'$ E., h = 114 m.

Lithologic foundation: sand 400 to 600 m. thick.

Equipment: Mainka bifilar horizontal pendulum, two comp.

Time service: "accuracy 1 sec."

STONYHURST, see BLACKBURN

STRASBOURG, FRANCE

Station Sismologique de l'Institut de Physique du Globe, inaugurated in 1899 and augmented in 1906.
Prof. Edmond Rothé, Director.
Henri Labrouste, Sub-Director.

Postal address: Station Sismologique de l'Institut du Physique de Globe, Rue Flerder 9, Strasbourg, France.

$\varphi = 48°35'05''$ N., $\lambda = 7°45'57''$ E., h = 135 m.

Lithologic foundation: gravel.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., Wiechert vertical-motion seismograph, mass 2,000 kg., Mainka bifilar horizontal pendulum, mass 450 kg., Galitzin aperiodic seismometer, with photo-galvanometric registration.

Time service: time is kept and marked by high grade clocks (Leroy, Riefler, Strasser) and compared by chronographic methods by means of radiotelegraphic signals from the Eiffel tower.

SUBIACO, ITALY

Seismologic Station, established lately, no further information available.

SWARTHMORE, PENNSYLVANIA

Sproul Observatory.
Prof. John A. Miller, Director.
Swarthmore College.

Postal address: Sproul Observatory, Swarthmore, Pennyslvania.

$\varphi = 39°54'23.3''$ N., $\lambda = 75°21'13.4''$ W., h = 59.4 m.

Lithologic foundation:

Equipment: Milne seismograph, E comp.

Time service: time comparisons are obtained by radiotelegraphic signals from Arlington, and also by transit observations; the time marking clock is kept accurate within 1 minute.

SYDNEY, N. S. W., AUSTRALIA

Government Observatory, seismologic service inaugurated in May, 1906, Prof. William Ernest Cooke, Government Astronomer.

Postal address: Government Observatory, Sydney, New South Wales. Australia.

$\varphi = 33^\circ 51' 41.1''$ S., $\lambda = 151^\circ 12' 25.1''$ E., h = ca. 42.7 m.

Lithologic foundation: sandstone.

Equipment: Milne seismograph, E comp.
Constants: $T_0 = 20$ sec., 1 mm. displacement = $0.23''$.

Time service: hourly time signals from the mean time clock of Sydney Observatory.

SYDNEY, N. S. W., AUSTRALIA

Riverview College Observatory, seismologic service inaugurated in March, 1909.
Dr. Edward Francis Pigot, Director of the Observatory.

Seismologic work supported in part privately and in part with aid from the Government.

Postal address: Riverview College Observatory, Sydney, New South Wales, Australia.

$\varphi = 33^\circ 49' 49''$ S., $\lambda = 151^\circ 09' 30''$ E., h = ca. 41.9 m.

Lithologic foundation: concrete piers, free of floor and soil, on sandstone (Triassic).

Equipment: and constants:		Mass	V	T_0	ϵ	r/T_0^2
Wiechert inverted pendulum,	N comp.,	1,000 kg.	158	8.4	5.5	0.018
" " "	E "	1,000 "	171	8.3	4.1	0.02
" vertical-motion pendulum,	Z "	80 "	83	5.1	5.5	0.05
Mainka horizontal pendulum,	N "	500 "	113	9.0	3.9	0.02
" " "	E "	500 "	148	10.2	2.1	0.04

Galitzin aperiodic seismometer, photo-galvanometric registration, three comp., to be installed.

Time service: time is kept and hour and minute time marks are made electromagnetically by a standard observatory mean time clock compared daily with the clock of the Government Astronomical Observatory.

*TACNA, CHILE

Seismologic Station.

Postal address: Servicio Sismolójico de Chile, Santiago, Chile.

$\varphi = 18°01'$ S., $\lambda = 70°18'$ W., h = 560 m.

Lithologic foundation: gravelly alluvium.

Equipment: Wiechert inverted pendulum, mass 180 kg., two comp. N and E.

Time service: time is kept and minute time marks are made by a contact clock compared weekly by telegraphic signals from the central station at Santiago.

TACUBAYA, MEXICO

Estación Seismológica Central, inaugurated September 5, 1910.

Ing. Francisco Patiño Ordáz, Jefe de la Estación Seismológica Central.
Servicio Seismológico Nacional de México,
Instituto Geológico Nacional.

Postal address: 4a de Zaragoza no. 127, Observatorio Astronómico Nacional, Estación Seismológica, Tacubaya, D. F., México, or Instituto Geológico Nacional, 6a del Cipres núm. 176, México, D. F., República Mexicana.

$\varphi = 19°24'18''$ N., $\lambda = 99°11'37''$ W., h = 2,320 m.

Lithologic foundation: volcanic series.

Equipment: and constants:		Mass		V	T_0	ϵ
Wiechert inverted pendulum,	N and E comp.,	17,000	kg.	2,000	1.5	2:5
" " "	N " E "	1,200	"	200	8.0	1:6
" " "	N " E "	200	"	80	5.0	3:5
" " "	N " E "	125	"	40	5.0	3:5
" vertical-motion pendulum,	Z "	1,300	"	160	4.0	3:5
Wiechert vertical-motion pendulum,	Z "	80	"	80	4.0	3:5
Omori horizontal pendulum,	N " E "	10	"			
Bosch-Omori horizontal pendulum,	N " E "	0.2	"			

Wiechert-Mintrop tromometer, phot. registr.

Schmidt trifilar gravimeter, phot. registr.

Time service: time is kept by the mean time clock of the Observatorio Astronómico Nacional within a probable error of 0.2 sec.; time marks are made by contact watches; the error of reading of the seismogram is ca. 0.5 sec.

TADOTSU, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1902. Y. Katsuno, Director.

Supported by the local prefecture.

Postal address: Tadotsu Meteorological Observatory, Tadotsu, Japan.

$\varphi = 34°17'$ N., $\lambda = 133°46'$ E., $h = 4$ m.

Lithologic foundation: soft ground, alluvial.

Equipment: Omori horizontal pendulum tromometer, mass 10 kg., two comp. N and E.

Constants: $V = 20$, $T_0 = 22$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

TAICHU, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1897.

Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi = 24°09'$ N., $\lambda = 120°41'$ E., $h = 78.4$ m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; also since June, 1902, Omori horizontal pendulum tromometer, mass 6 kg., E comp.

Constants: $V = 6$, $T_0 = 12$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

TAIHOKU, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1896. Prof. H. Kondo, Director.

Chief Station of the Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi = 25°02'$ N., $\lambda = 121°31'$ E., $h = 9.3$ m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; also, since June, 1901, Omori horizontal pendulum tromometer, two comp. N and E.

Constants:	Mass	V	T_0
N,	55 kg.	120	8 sec.
E,	16 "	20	25 "

Time service: time is kept by astronomical clocks (Riefler) and chronometers; time comparisons are made by astronomical observations.

Reports are received from more than 100 rainfall stations regarding "felt" shocks.

TAINAN, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1897.
Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi = 23°00'$ N., $\lambda = 120°12'$ E., h = 14.3 m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; also since January, 1902, Omori horizontal pendulum tromometer, mass 6 kg., E comp.
Constants: $V = 6$, $T_0 = 12$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

TAITO, FORMOSA, JAPAN

Meteorological Observatory, seismologic service inaugurated in 1901.
Meteorological Service of Formosa.

Postal address: Taihoku Meteorological Observatory, Taihoku, Formosa, Japan.

$\varphi = 22°45'$ N., $\lambda = 121°09'$ E., h = 9.9 m.

Lithologic foundation: alluvial.

Equipment: Gray-Milne seismograph; also since December, 1903, Omori horizontal pendulum tromometer, mass 6 kg., E comp.
Constants: $V = 6$, $T_0 = 12$ sec.

Time service: telegraphic time signals received from the Taihoku central station.

TAKAYAMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in October, 1915.

R. Wakazaki, Director.
Supported by the local prefecture.

Postal address: Takayama Meteorological Observatory, Takayama, Japan.

$\varphi = 36°09'$ N., $\lambda = 137°16'$ E., h = 560.3 m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: V = 50, $T_0 = 3$ sec.

Time service: time comparisons obtained daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

*TANANARIVE, MADAGASCAR

Observatoire des P. P. Jésuites, reconstructed in 1898.

Postal address: Tananarive, Madagascar.

$\varphi = 18°55'02''$ S., $\lambda = 47°31'45''$ E., h = ca. 1,402 m.

Lithologic foundation: red clay and gneiss.

Equipment: Cecchi seismograph.

TARANTO, ITALY

Osservatorio Geodinamico Taranto, seismologic service inaugurated in 1908.
Luigi Ferraiolo, Director.

Postal address: Osservatorio, Taranto, Italia.

$\varphi = 40°28'30''$ N., $\lambda = 17°15'15''$ E., h = 15.85 m.

Lithologic foundation: limy gravel (Upper Pliocene).

Equipment: and constants:	Mass	V	T_0	
Wiechert inverted pendulum,	200 kg.	120	8 sec.	60 cm. = 1 hr.
Vicentini horizontal seismograph,	100 "	100	2.4 "	
" vertical "	50 "	120	0.8 "	
Cartuja horizontal pendulum,	350 "	25	16.0 "	
" vertical "	350 "	250	0.6 "	

Time service: time comparisons by radiotelegraphic signals from Paris.

*TAŠKENT, TURKESTAN, RUSSIA

Seismologic Station, a station of the first class of the Russian service.
Astronomical and Physical Observatory.

Postal address: Seismologic Station, Astronomical and Physical Observatory, Taškent, Turkestan, Russia.

$\varphi = 41°19.5'$ N., $\lambda = 69°17'42''$ E., h = 478 m.

Lithologic foundation: stiff loess. (Mounted in a special building.)

Equipment: Repsold-Zöllner horizontal pendulum, mass 59 grams, two comp.
Constants: $V = 60$, $T_0 = 9$ sec.
Bosch-Omori horizontal pendulum, mass 11 kg., two comp.
Constants: $V = 10$, $T_0 = 12$ sec.
Milne seismograph.

Time service: of the Astronomical Observatory.

TEMESVAR, see TEMIȘOARA

TEMIȘOARA, ROUMANIA

Seismologic Station.
Fundatiunea Konkoly.

Postal address: Fundaţiunea Konkoly, Temișoara, Romània.

$\varphi = 45°46'$ N., $\lambda = 21°14'$ E., h = 103 m.

Lithologic foundation:

Equipment: Konkoly-Vicentini seismograph, mass 180 kg., two comp. N and E.
Konkoly-Vicentini seismograph, mass 60 kg., Z comp.

Time service: not stated.

*TIFLIS, RUSSIA

Seismologic Station, a station of the first class of the Russian service.

Postal address: Seismologic Station, Physical Observatory, Tiflis, Russia.

$\varphi = 41°43'08''$ N., $\lambda = 44°47'51''$ E., h = 409 m.

Lithologic foundation: slaty shales on hard rock.

Equipment: Ehlert triple horizontal pendulum, mass 75 grams. Milne seismograph, mass 0.23 kg., E comp. Four Bosch-Omori horizontal pendulums, mass 10 kg., two sets of two comp. Heavy Zöllner horizontal pendulum, mass 14 kg., two comp. Cancani vertical (simple) pendulum, mass 300 kg., two comp.

TIGAON, AMBOS CAMARINES, PHILIPPINE ISLANDS

Meteorological Station, seismologic service inaugurated in May, 1918.
Fabián Martinez, Observer.
Weather Bureau, Philippine Islands.

Postal address: The Meteorological Station, Tigaon, Ambos Camarines, P. I., or Manila Observatory, Manila, P. I.

$\varphi = 13°36'$ N., $\lambda = 123°28'$ E., $h = 35.8$ m.

Lithologic foundation: andesite and basalt.

Equipment: Vicentini system, Manila type.

Time service: time comparisons daily by telegraphic signals; no chronograph.

TOKUSHIMA, JAPAN

Meteorological Observatory, seismologic service inaugurated in March, 1913.
G. Jimba, Director.
Supported by the local prefecture.

Postal address: Tokushima Meteorological Observatory, Tokushima, Japan.

$\varphi = 34°04'$ N., $\lambda = 134°33'$ E., $h = 2.9$ m.

Lithologic foundation: soft ground.

Equipment: Omori horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V = 50$, $T_0 = 2.4$ sec.
Imamura seismograph, two comp. N and E.
Constants: $V = 2$, $T_0 = 4.6$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

TOKYO, JAPAN

Central Meteorological Observatory of Japan, seismologic service inaugurated 1920 (?).
K. Nakamura, Director.

Postal address: Central Meteorological Observatory of Japan, Tokyo, Japan.

$\varphi = 35°41'06''$ N., $\lambda = 139°45'04''$ E., $h = 21.3$ m.

Lithologic foundation: (Quaternary).

Equipment: Wiechert inverted pendulum, two comp. N and E. Omori horizontal pendulum.

Constants:	V	T_0	ϵ	r/T_0^2
Wiechert N,	76	3.0 sec.	3.2	0.0001
" E,	80	3.0 "	3.2	0.0001
Omori,	20	16.1		0.017

Time service: not available, presumably excellent.

TOKYO, JAPAN

Seismological Institute, inaugurated in 1880.
Prof. Dr. Fusakichi Omori, Professor of Seismology, Director.
Tokyo Imperial University.

Postal address: Seismological Institute, Tokyo Imperial University, Tokyo, Japan.

$\varphi = 35°42'40''$ N., $\lambda = 139°45'59''$ E., h = 18.9 m.

Lithologic foundation: clay (diluvium).

Equipment:

Omori horizontal pendulum,	N comp.,	$V=120$, $T_0=20$ sec.
" " "	E "	$V=120$, $T_0=20$ "
" " "	N "	$V=20$, $T_0=40$ "
" " "	E "	$V=30$, $T_0=40$ "
" " "	E "	$V=15$, $T_0=60$ "
" " "	N "	$V=10$, $T_0=30$ "
" " "	E "	$V=10$, $T_0=30$ "
" " "	N "	$V=300$, $T_0=8$ "
" " "	E "	$V=300$, $T_0=8$ "
" duplex pendulum, resultant horizontal motion,		$V=20$, $T_0=14$ "
" vertical motion seismograph,	Z comp.,	$V=20$, $T_0=18$ "
" " " "	Z "	$V=10$, $T_0=22$ "

Time service: time marks are made by a contact chronometer checked daily by radiotelegraphic time signals from the Tokyo Astronomical Observatory.

TOLEDO, SPAIN

Estación Sismológica Principal de Toledo.
Vicente Inglada Ors, Ingeniero Geógrafo, Director.
Instituto Geográfico y Estadístico.

Postal address: Ingeniero Jefe de la Estación Sismológica de Toledo, España.

$\varphi = 39°51'25.6''$ N., $\lambda = 4°01'28.5''$ W.. h = 500 m.

Lithologic foundation: gneiss.

Equipment: and constants:

			Mass	V	T_0	ϵ	r/T_0^2	m.per hour
Vicentini	seismograph,	N comp.,	100 kg.	112	2.5		0.004	0.6
“	“	E “	100 “	111	2.5		0.004	0.6
“	“	Z “	50 “	250	0.86		0.020	0.6
Agamennone[1]	“	NE “	2,000 “	230	2.5		0.010	0.61
“ [1]	“	NW “	2,000 “	230	2.5		0.010	0.61
Bosch-Omori	“	N “	25 “	20	17.0		0.001	0.9
“ “	“	E “	25 “	20	17.0		0.001	0.9
Wiechert	“	NE “	1,000 “	190	8.9	5	0.003	0.9
“	“	NW “	1,000 “	225	8.2	5	0.004	0.9
Milne	“	E “		9	15.0			0.255
Rebeur-Ehlert	“	N “	0.2 “	123	7.0	4		0.86
“ “	“	E “	0.2 “	122	7.0	4		0.86

Time service: time is kept by a Dent clock compared by radiotelegraphic signals from the Eiffel tower; minute marks are made electromagnetically by several contact clocks as follows,—a Bosch clock for the Bosch-Omori seismographs, a Bosch clock for the Milne and Rebeur-Ehlert seismographs (which register photographically), and a Hipp clock for the Vicentini, Agamennone, and Wiechert instruments; accuracy of time ca. 0.5 sec.

[1] May be adjusted to magnify 1,000 times.

TORONTO, CANADA

Meteorological Office, seismologic service inaugurated in September, 1897. Sir Frederick Stupart, Director, Dominion Meteorological Service.

Department of Marine and Fisheries.

Postal address: Director, Dominion Meteorological Service, Toronto, Canada.

$\varphi=43^\circ40'00.8''$ N., $\lambda=79^\circ23'54''$ W., h=ca. 115.5 m.

Lithologic foundation: sand and gravel on boulder clay to a depth of ca. 15 m., then shale over crystalline rock (Laurentian) at a depth of ca. 335.5 m.

Equipment: Milne seismograph,[2] mass 0.23 kg., E comp., no damping. Constants: $T_0=18$ sec., 1 mm. displacement $=0.45''$.

Time service: time is kept and marked by a clock whose rate may vary ±2 sec.; time comparisons are made by meridian transit observations with an accuracy of ±0.01 sec.

[2] Soon to be superseded by a Milne-Shaw seismograph to register two horizontal comp. N and E.

TORTOSA, SPAIN

Observatorio del Ebro, seismologic service inaugurated in 1905.
Pedro Trullás, in charge.
Observatorio del Ebro.

Postal address: Observatorio del Ebro, Tortosa, España.

$\varphi = 40°49'14''$ N., $\lambda = 0°29'38''$ E., h = 39 m.

Lithologic foundation: conglomerate (Miocene).

Equipment: and constants:			Mass	V	T_0
Vertical (simple)	pendulum,	N comp.	300 kg.	200	2.4 sec.
Vicentini	"	E "	100 "	90	2.5 "
"	"	Z "	50 "	150	0.65 "
Mainka horizontal[1]	"	N "	1,500 "	160	15.0 "
" "[1]	"	E "	150 "	50	7.5 "

Time service: time is kept and minute time marks are made electromagnetically by the central Observatory clock.

[1] Modified.

*TOULOUSE[2], FRANCE

Observatoire de l'Université.

Postal address: Toulouse, France.

$\varphi = 43°36'46''$ N., $\lambda = 1°27'44''$ E., h = 194 m.

Lithologic foundation: sandstone and marl (Miocene).

[2] There is now no station at Toulouse.

TRENTA (COSENZA), ITALY

Stazione Sismica "Proviero," inaugurated in February, 1915.
D. Antonio Proviero, Director.

Postal address: Stazione Sismica "Proviero," Trenta (Cosenza), Italia.

$\varphi = 39°16'57.57''$ N., $\lambda = 16°19'21.3''$ E., h = 534.43 m.

Lithologic foundation: friable sedimentary rock, prevailingly calcareous.

Equipment: Agamennone seismometrograph, mass 50 kg., three comp.
Constants: $V = 50$; T_0 (horizontal) = 7 sec., T_0 (vertical) = 1.8 sec.
Vertical microseismometrograph, mass 1,000 kg.
Constants: $V = 250$, $T_0 = 2.8$ sec.

Time service: time is kept (and marked?) by a marine chronometer compared by meridian observations.

TRIESTE, ITALY

R. Instituto Geofisico[1].
Prof. Francisco Vercelli, Director.
Comitato Talassografico Italiano.

Postal address: R. Instituto Geofisico, Passegio S. Andrea 2, Trieste, Italia.

$\varphi = 45°39'$ N., $\lambda = 13°46'$ E., h = 67 m.

Lithologic foundation: calcareous rocks.

Equipment: Wiechert inverted pendulum, mass "1 ton" (1,000 kg.?), two horiz. comp.
Constants: V = ca. 200, $T_0 = 12$ sec.
Vicentini seismograph, three comp.
Constants:

		V	T_0
N comp.,	100 kg.	100	1.6 sec.
E "	100 "	100	1.6 "
Z "	80 "		1.0 "

Time service: not stated.

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[1] The seismologic station is to be transferred to another locality in the city. The chronographic system will be changed.

TSINGTAO, CHINA (JAPAN)

The Meteorological Observatory of Tsingtao, seismologic work renewed January 1, 1921, after being interrupted for about six years.
T. Irumata, Director.

Postal address: The Meteorological Observatory of Tsingtao, Tsingtao, China.

$\varphi = 36°04'11''$ N., $\lambda = 120°19'14''$ E., h = 70 m.

Lithologic foundation: igneous rock.

Equipment: Wiechert inverted pendulum, mass 200 kg.

Time service: time comparisons are made by transit observations using a chronograph; accuracy ca. 0.1 sec.

*TSITA, SIBERIA, RUSSIA

Seismologic Station.

$\varphi = 52°01'$ N., $\lambda = 113°30'$ E.

TSU, JAPAN

Meteorological Observatory, seismologic service inaugurated in March, 1917.

S. Yasaki, Director.

Supported by the local prefecture.

Postal address: Tsu Meteorological Observatory, Tsu, Japan.

$\varphi = 34°43'$ N., $\lambda = 136°31'$ E., h = 3.0 m.

Lithologic foundation: soft sandy soil.

Equipment: C. M. O. horizontal pendulum tremor recorder, two comp. N and E.
Constants: $V = 20$, $T_0 = 10$ sec.

Time service: time comparisons daily by radiotelegraphic signals from the Tokyo Astronomical Observatory.

TSUKUBA-SAN, JAPAN

Meteorological Observatory, seismologic service inaugurated at sub-station (a) in November, 1904; and at sub-station (b) in January, 1902
Z. Sato, Director.

Supported by the Central Meteorological Observatory.

Postal address: Tsukuba-san Meteorological Observatory, Tsukuba-san Ibaraki-ken, Japan.

Sub-station (a), $\varphi = 36°13'$ N., $\lambda = 140°06'$ E., h = 870 m.
" " (b), $\varphi = 36°12'$ N., $\lambda = 140°06'$ E., h = 240 m.

Lithologic foundation: sub-station (a), diorite.
" " (b), decomposed diorite.

Equipment: at sub-station (a), Omori horizontal pendulum tromometer, two comp. both E.
Constants: E, $V = 7$, $T_0 = 13$ sec.; E, $V = 30$, $T_0 = 5$ sec.
At sub-station (b), Omori horizontal pendulum tremor recorder, E comp.
Constants: $V = 200$, $T_0 = 9$ sec.

Time service. time comparisons obtained daily by radiotelegraphic signals from Tokyo Astronomical Observatory.

TUCSON, ARIZONA

Tucson Magnetic Observatory, seismologic service inaugurated in September, 1910.

Magnetic Observer, in charge; W. H. Cullum, present incumbent.

U. S. Coast and Geodetic Survey.

Postal address: Tucson Magnetic Observatory, R. F. D. No. 2, Tucson. Arizona, or U. S. Coast and Geodetic Survey, Washington. D. C.

$\varphi = 32°14'48''$ N., $\lambda = 110°50'06''$ W., h = 770 m.

Lithologic foundation: concrete piers on sand and loose gravel.

Equipment: Bosch-Omori seismograph, mass 10 kg., two comp. N and E.
Constants: $V = 10$, $T_{0N} = 18$ sec., $T_{0E} = 17$ sec.

Time service: two box chronometers, corrections and rates determined once a week from telegraphic time signals from Tucson. The times of starting and stopping the record are noted daily by one of the chronometers. The seismograph clock, which makes a mark on the smoked paper each minute (1 minute = 15 mm.) is not of high grade and the daily rate is somewhat irregular so that the times of the minute marks in the middle of the sheet may at times be in error by a considerable amount.

*TURIN, ITALY

Seismologic Station discontinued, and apparatus transferred to Porto Maurizio about 1910.

UCCLE, BELGIUM

Station sismologique, inaugurated in January, 1904.

Professor G. Lecointe, Director of the Observatory.
Observatoire royal de Belgique.

Postal address: Observatoire royal, Uccle, Belgique.

$\varphi = 50°47'55.5''$ N., $\lambda = 4°21'31''$ E., h = 100 m.

Lithologic foundation: limestone (calcaire grossier, Eocene).

Equipment: Galitzin aperiodic seismometer, photo-galvanometric registration, two comp. N and E.

Wiechert inverted pendulum, mass 1,000 kg., two comp.
Wiechert vertical-motion seismograph, mass 1,300 kg.

For constants,—see Annales de l'Observatoire Royale de Belgique, nouvelle série, Physique du globe, tome VI, fasc. II, pp. 163 et seq.

Time service: minute time marks are made electromagnetically by a contact clock which is compared, to an accuracy of ca. 0.1 sec., with the precision clock of the time service of the Observatory. The time marks are made by eclipsing the light beams, or lifting the writing styles.

*UNGVÁR, CZECHOSLOVAKIA

Observatoire sismologique, inaugurated in 1911.
Lycée royale catholique.

Postal address: Observatoire sismologique, Lycée royale catholique, Ungvár, Czechoslovakia.

$\varphi = 48°37'$ N., $\lambda = 22°14'$ E., h = 128 m.

Equipment: Bosch-Omori horizontal pendulum, mass 10 kg., two comp.

UPSALA, SWEDEN

Meteorological Observatory of the University, seismologic service inaugurated in 1904.

Prof. Filip Åkerblom, Director.

Postal address: Meteorological Observatory, Upsala, Sweden.

$\varphi = 59°51'29''$ N., $\lambda = 17°37'37''$ E., h = 14 m.

Lithologic foundation: granite pier resting directly on crystalline rock.

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E.

Constants:	L	J	V	T_0	ϵ	r
N,	23.9	4,510	189	9.8 sec.	3.7	0.5
E,	22.0	4,204	191	9.4 "	3.7	0.6

Time service: minute time marks are made by an interruption in the registration; time is checked at least once a week with a chronometer at the Astronomical Observatory near by.

URBINO, ITALY

Osservatorio Meteorico-Sismico di Urbino, founded in 1853.

Prof. Giovanni Camburini, Director.
Ufficio Centrale di Meteorologia e Geodinamica, Roma.

Postal address: Osservatorio Meteorico-Sismico, Urbino, Italia.

$\varphi = 43°43'$ N., $\lambda = 12°38'$ E., h = 451.5 m.

Lithologic foundation: argillaceous marl.

Equipment: at present this station functions solely as a meteorological station.

Time service: not stated.

VENICE, ITALY

Stazione Sismologica, inaugurated in December, 1904.

Prof. Padre Francisco Saverio Zanon, Director of the Observatory.
Seminario Patriarcale di Venezia.

Postal address: Osservatorio Meteorologico e Geodinamico del Seminario Patriarcale di Venezia, Venezia, Italia.

$\varphi = 45°25'44''$ N., $\lambda = 12°20'15''$ E., h = 1 m.

Lithologic foundation: argillaceous rock.

Equipment: Vicentini microseismograph, three comp.
Constants: (horizontal comps.) Mass = 100 kg., length of pendulum = 1.5 m. $V = 120$, $T_0 = 2.4$ sec., 5 mm. = 1 minute: (vertical comp.) mass = 50 kg., length of spring = 1.29 m., $V = 140$, $T_0 = 0.8$ sec., 5 mm. = 1 minute.
Agamennone seismoscope.

Time service: time is kept and marked by a good contact clock provided with a mercury-compensated pendulum, compared with good chronometers; accuracy ca. 1 sec.

VERA CRUZ, MEXICO

Estación Seismológica de Veracruz, a station of the second order.

Ing. Rubén Bouchez, Jefe de la Estación.
Servicio Seismológico Nacional de México,
Instituto Geologico Nacional.

Postal address: Instituto Geológico Nacional, 6a del Cipres núm. 176 México, D. F., República Mexicana.

$\varphi = 19°12'$ N., $\lambda = 96°07'58''$ W., $h = 5$ m.

Lithologic foundation: basalt.

Equipment: Wiechert inverted pendulum, mass 200 kg., two comp. N and E. Wiechert vertical-motion seismograph, mass 80 kg., Z comp.

Time service: time comparisons by telegraphic signals from Tacubaya.

*VERNYI (WJĖRNOJE), RUSSIAN TURKESTAN

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 43°17'$ N., $\lambda = 76°57'$ E.

Equipment: Galitzin seismograph, mech. registr. three comp.

*VERONA, ITALY

Stazione Sismica del R. Instituto Technico, inaugurated in 1906.

Postal address: Verona, Italia.

$\varphi = 45°26'$ N., $\lambda = 11°01'$ E., $h =$ ca. 60 m.

Lithologic foundation: sandy alluvium.

Equipment: Vicentini microseismograph, mass 150 kg., two horizontal comp.
Constants: $V = 65$, $T_0 = 2.4$ sec.
Vicentini seismograph, three comp.

Time service: time is checked with the clock of the telegraph office.

VESUVIUS, see NAPLES

VICTORIA. BRITISH COLUMBIA, CANADA

Meteorological Observatory, Gonzales Heights, seismologic service inaugurated (at present site) in April, 1914.
F. Napier Denison, Director.
Dominion Meteorological Service, Department of Marine.

Postal address: Meteorological Observatory, Victoria, B. C., Canada.

$\varphi = 48°24'50''$ N., $\lambda = 123°19'28''$ W., h = ca. 67.6 m.

Lithologic foundation: cement piers, free of the floor, through a "cushion" of sand (18 inches thick) to igneous rock.

Equipment: Milne seismograph, older type, E comp. $T_0 = 18$ sec.
Wiechert vertical-motion seismograph, mass 80 kg., $V = 70$, $T_0 = 5$ sec.
Milne-Shaw seismographs to be installed (before end of 1920).

Time service: time is determined by astronomical observations and kept to an accuracy of 0.1 sec. Hourly time eclipses are made on the Milne record by a watch, and minute time marks are made electromagnetically on the Wiechert record by a good contact pendulum clock which has a steady rate (1 sec. per day).

*VIENNA, AUSTRIA

Zentralanstalt für Meteorologie und Geodynamik, seismologic service inaugurated in 1905.
Prof. Dr. Exner, Director.

Postal address: Zentralanstalt für Meteorologie und Geodynamik, Wien, Österreich.

$\varphi = 48°14'53''$ N., $\lambda = 16°21'42''$ E., h = ca. 200 m.

Lithologic foundation: concrete piers in a cellar on alluvium.

Equipment: Wiechert inverted pendulum, mass 1,000 kg.
Wiechert vertical-motion seismograph, mass 1,300 kg.
Vicentini seismograph, three comp.

VIEQUES, PORTO RICO

Porto Rico Magnetic Observatory, seismologic service inaugurated in September, 1903.
Magnetic Observer, in charge, W. W. Merrymon, present incumbent.
U. S. Coast and Geodetic Survey.

Postal address: Porto Rico Magnetic Observatory, Vieques, Porto Rico, or U. S. Coast and Geodetic Survey, Washington, D. C.

$\varphi = 18°08'50''$ N., $\lambda = 65°26'50''$ W., $h = 19.08$ m.

Lithologic foundation: granitic rock overlaid with a few feet of heavy clay loam.

Equipment: Bosch-Omori seismograph, mass 10 kg., two comp. N and E.
Constants: $V = 10$, $T_{oN} = 19$ sec., $T_{oE} = 17$ sec., 15 mm. = 1 minute.

Time service: two box chronometers, corrections and rates determined by solar observations 3 or 4 times a month. The times of starting and stopping the record are noted daily by one of the chronometers and also the time of a mark made about the middle of a day's record. The seismograph clock, which makes a mark each minute on the smoked paper (1 minute = 15 mm.), is not of high grade, but when in good adjustment has a fairly uniform rate, so that the times of the minute marks are probably uncertain by not more than 5 sec.

*VLADIVOSTOK, RUSSIA

A seismologic station of the first class of the Russian service was projected here.

VOLCANO HOUSE, T. H.

Hawaiian Volcano Observatory, seismologic service inaugurated in August, 1912.
Dr. T. A. Jaggar, Volcanologist, in charge.
U. S. Weather Bureau.

Postal address: Hawaiian Volcano Observatory, Volcano House, T. H. or U. S. Weather Bureau, Washington, D. C.

$\varphi = 19°25'54.2''$ N., $\lambda = 155°15'39.2''$ W., $h = 1214.6$ m.

Lithologic foundation: concrete piers on basalt.

Equipment: Bosch-Omori horizontal pendulums (re-built at the station) both registering on one speeded drum (12 hour record), mass 100 kg., two comp. N and E, adjusted to register local shocks.
Constants: $V = 116$, $T_o = 7$ sec., aperiodic (oil-damping), $r/T_o^2 = 0.03$.
Romberg-Omori horizontal pendulum, optical registration, 24-hour record, viscous (oil) coupling, oil damping, silk-fibre mirror suspension, wire suspension of steady mass, adjusted for teleseismic registration.
Constants: $V = 124$, $T_o = 18.4$ sec., $K_o = 0.45$ (Cf. Bull. Seis. Soc. Am., IX, 4, 136).

A special vertical-component pendulum, optical registration, is set up but not finished.

Time service: time is kept by a chronometer checked occasionally by radiotelegraphic signals at Hilo. Provision is being made for direct receipt of radiotelegraphic signals.

WASHINGTON, D. C.

Georgetown University Seismological Station[1], inaugurated in 1911. Rev. Francis A. Tondorf, S.J., Chief Seismologist.

Postal address: Georgetown University Seismological Station, W. Washington, D. C.

$\varphi = 38°54'25''$ N., $\lambda = 77°04'24''$ W., h = 42.4 m. at substation A, h = 48.2 m. at substation B.

Lithologic foundation: decayed diorite.

Equipment: Wiechert inverted pendulum, mass 200 kg., two comp. N and E.
Constants: N, $V = 142$, $T_0 = 5.2$ sec.; E, $V = 165$, $T_0 = 5.4$ sec.
Wiechert vertical-motion seismograph, mass 80 kg., Z comp.
Constants: Z, $V = 80$, $T_0 = 3$ sec.
Bosch-Omori horizontal pendulum, mass 25 kg., two comp. N and E.
Constants: N, $V = 13.5$, $T_0 = 8.6$ sec.; E, $V = 13.7$, $T_0 = 8.8$ sec.
Bosch horizontal pendulum, mass 0.2 kg., phot. registr., two comp. N and E.
Constants: $V = 133$, $T_0 = 5.0$ sec.
Mainka bifilar horizontal pendulum, mass 135 kg., two comp. N and E.
Constants: N, $V = 70$, $T_0 = 5.4$ sec.; E, $V = 93$, $T_0 = 4.0$ sec.

Time service: time is kept and hour and minute time marks are made electromagnetically by a contact clock; time comparisons are made by communication with the Georgetown Astronomical Observatory, by telegraphic time signals (Western Union service), and by radiotelegraphic signals (Arlington service).

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[1] This station also maintains a substation at Guatemala City, Guatemala, with a Wiechert inverted pendulum, mass 80 kg.

WASHINGTON, D. C.

Seismologic Station, U. S. Weather Bureau.
Dr. W. J. Humphreys, Professor of Meteorological Physics, in charge.

Postal address: U. S. Weather Bureau, Washington, D. C.

$\varphi = 38°54'12''$ N., $\lambda = 77°03'03''$ W., h = 21 m.

Lithologic foundation: clay (few meters) over granitic rock.

Equipment: Marvin inverted pendulum, two comp. N and E.

Constants: $V=110$, $T_0=6.4$ sec., 1 mm. = 4 sec.

Time service: time is kept and minute marks are made electromagnetically by the writing styles by a contact clock of special construction compared daily by time signals from the U. S. Naval Observatory.

WELLINGTON, NEW ZEALAND

Hector Observatory, seismologic service inaugurated in 1898.
Dr. Charles Edward Adams, Government Astronomer and Seismologist.
Department of Internal Affairs, New Zealand Government.

Postal address: Government Astronomer, Hector Observatory, Wellington, New Zealand.

$\varphi=41°17'03.8''$ S., $\lambda=174°46'04''$ E., h = ca. 121.9 m.

Lithologic foundation: graywacke and argillite (Trias-Jura).

Equipment: Milne seismograph, mass 0.222 kg., E comp.
Constants: $L=15.6$ m., $J=525$ m., $V=6.1$, $T_0=18$ sec., $\epsilon=0.14$.
A Milne-Shaw pendulum is soon to be installed.
Gray-Ewing duplex pendulum.
Tilt is measured by a sensitive spirit level mounted E–W on the pier, and also by the stride level of the transit instrument.

Time service: time is determined astronomically and comparison signals are put on the seismogram at least five times per day direct from the standard clock. Ordinary time marks are made by eclipse of the light beam once each hour.

WELTEVREDEN, BATAVIA, JAVA

Batavia Observatory, seismologic service inaugurated in June, 1898.

Postal address: Director, Koninklijk Magnetisch en Meteorologisch Observatorium, Weltevreden, Java.

$\varphi=6°11'00''$ S., $\lambda=106°49'50''$ E., h = 8 m.

Lithologic foundation: alluvium (Pleistocene).

Equipment:
Milne seismograph, since June 1, 1898.
Bosch seismograph, two comp. N and E, installed in 1912.
Wiechert inverted pendulum, mass 1,000 kg., two comp. N and E, installed December 6, 1908.

Constants:	V	T_0	ϵ
N,	ca. 193	ca. 8.0s.	ca. 5
E.	ca. 216	ca. 7.6	ca. 5

Time service: time is kept (?) and minute time marks are made electromagnetically by a lifting of the writing styles by a Peyer Favager contact clock, with an accuracy of about 1 sec.; hour time marks are made by the observer on duty by lifting the styles electromagnetically.

WEST BROMWICH, ENGLAND

Private seismologic station, inaugurated in 1908.
J. J. Shaw, proprietor.

Postal address: Birmingham Road, West Bromwich, England.

$\varphi = 52°31'$ N., $\lambda = 1°59'$ W., h = ca. 156 m.

Lithologic foundation:

Equipment: Omori seismograph, mech. registr., two comp. N and E.
Constants: $V = 60$, $T_0 = 12$.
Milne-Shaw instruments frequently running on test.

Time service: an observatory clock, rate about 2 sec. per week, compared daily by radiotelegraphic signals.
The primary objective of this station is construction, testing, and research,—not routine registration.

WINNIPEG, see ST. BONIFACE

WJERNOJE, see VERNYI

*WORCESTER, MASSACHUSETTS

Seismologic Station, inaugurated in 1909.
Rev. William R. Cullen, S.J., Director.
Holy Cross College.

Postal address: Seismologic Station, Holy Cross College, Worcester, Massachusetts.

$\varphi = 42°16'23''$ N., $\lambda = 71°48'27''$ W., h = ca. 203.4 m.

Equipment: Wiechert inverted pendulum, mass 200 kg.

YAGI, JAPAN

Meteorological Observatory, seismologic service inaugurated in June, 1917.
H. Haraoka, Director.
Supported by the local prefecture.

Postal address: Yagi Meteorological Observatory, Yagi, Nara-ken, Japan.

$\varphi = 34°31'$ N., $\lambda = 135°48'$ E., h = 63.3 m.

Lithologic foundation:

Equipment: C. M. O. horizontal pendulum tremor recorder, two comp. N and E.

Constants: $V=30$, $T_0=6$ sec.

Time service: time comparisons by telegraphic signals received through the local post-office from the Tokyo Astronomical Observatory.

YAMAGATA, JAPAN

Meteorological Observatory, seismologic service inaugurated in September, 1913.
M. Morita, Director.

Supported by the local prefecture.

Postal address: Yamagata Meteorological Observatory, Yamagata, Japan.

$\varphi=38°15'$ N., $\lambda=140°21'$ E., $h=150.6$ m.

Lithologic foundation: soft ground.

Equipment: Imamura seismograph, two comp. N and E.
Constants: $V=2$, $T_0=4$.

Time service: time corrections by telegraphic signals received through local post-office from Tokyo Astronomical Observatory.

ZAGREB (AGRAM), JUGOSLAVIA

R. Meteorological and Geodynamical Observatory, seismologic service inaugurated in 1906.
Dr. A. Mohorovičić, Provisory Director.

Postal address: R. Meteorological and Geodynamical Observatory, Zagreb, Jugoslavia.

$\varphi=45°48'55''$ N., $\lambda=15°58'52''$ E., $h=155$ m.

Lithologic foundation: clay (alluvium 40 to 50 m. thick).

Equipment: Wiechert inverted pendulum, mass 1,000 kg., two comp. NW and NE.
Constants: $V=200$, $T_0=9$ to 10 sec., $\epsilon=5$ to 6, $r=0.1$ to 0.2 mm., $r/T_0^2=$ 0.001 to 0.002, 20 mm. = 1 minute.
Wiechert inverted pendulum, mass 80 kg., two comp. NW and NE.
Constants: $V=20$, $T_0=7$ sec., $\epsilon=5$ to 6, $r=0.1$ mm.

Time service: time is kept to an accuracy of 0.1 to 0.2 sec. by a Riefler clock.

ZANTE, GREECE

Seismologic Station, inaugurated in 1900.
Prof. Dennis Martinengo, Director.
Observatoire National d'Athènes.

Postal address: Station Sismologique, Zante, Grèce.

$\varphi = 37°39'$ N., $\lambda = 18°40'$ E., h = ca. 4 m.

Lithologic foundation: land reclaimed from the sea.

Equipment: Agamennone seismograph, temporarily out of use.

Time service: not stated.

ZI-KA-WEI, SHANGHAI, CHINA

Zi-ka-wei Observatory, seismologic service inaugurated in 1903, and augmented in 1909 and 1913.
Louis Froc, S.J., Director.
Jesuit Mission of Nanking.

Postal address: Zi-ka-wei Observatory, via Shanghai, China.

$\varphi = 31°11'32''$ N., $\lambda = 121°25'48''$ E., h = 7 m.

Lithologic foundation: alluvium several meters thick.

Equipment: Omori horizontal pendulum, mass 20 kg., two comp. N and E., 13 mm. = 1 minute. Installed in 1903.
Wiechert inverted pendulum, mass 1,200 kg., two comp. N and E, 15 mm. = 1 minute. Began registration March 31, 1909.
Galitzin aperiodic vertical-motion seismometer, photo-galvanometric registration, 30 mm. = 1 minute. Began registration April 3, 1913.
Constants: (May 3, 1920, presumably of Wiechert apparatus)

	V	T_0	ϵ	r/T_0^2
N,	137	11 sec.	2.8	0.013
E,	131	11 "	3.2	0.011

Time service: the clocks are compared daily with the astronomical clocks (Férron) of the time service of the Observatory.

ZÜRICH, SWITZERLAND

Erdbeben-Warte Zürich, inaugurated in 1911. (Macroscopic observations since 1898.) The special purpose of this station is the registration of local and near earthquakes.
Prof. Dr. Alfred de Quervain, Director.
Dr. A. de Weck, Assistant.
Bureau Météorologique Central Suisse.

Postal address: Schweizerischer Erdbebendienst, Météorolog. Centralanstalt, Zürich, Schweiz.

$\varphi = 47°22'07.2''$ N., $\lambda = 8°34'49.5''$ E., $h = 604.2$ m.

Lithologic foundation: sandstone and marl (Samartien, Miocene).

Equipment: Bosch-Mainka horizontal pendulum, mass 450 kg., two comp. N and E.
Constants: $V = 220$, $T_0 = 5$ sec., $\epsilon = 4$.
Wiechert vertical-motion seismograph, mass 80 kg., Z comp.
Constants: $V = 110$, $T_0 = 3.2$ sec., $\epsilon = 4$.
Quervain-Piccard transportable seismograph[1], three comp., mass 25 kg.
Constants: $V = 50$, $T_0 = 2$ sec.
Quervain-Piccard seismograph for local earthquakes, in construction, mass 20,000 kg., three components.
Constants: $V = 1{,}000$ to $2{,}000$, $T_0 =$ ca. 3 sec.

Time service: time is kept by excellent compensated astronomical clocks compared daily by radiotelegraphic signals from the Eiffel tower with an accuracy of about 0.1 sec.; the seismograms are read with an accuracy of about 0.1 sec. for the horizontal motion and of about 0.3 sec. for the vertical motion.

Publication: preliminary measurements of the principal phases are published in the daily Meteorological Bulletin of the Météorolog. Centralanstalt and collected in an annual report sent to all seismologic observatories which desire it.

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[1] For the registration of epicentral shocks and jarring due to artificial causes.

*ZURNABAD, RUSSIA

Seismologic Station, a station of the second class of the Russian service.

$\varphi = 40°31'$ N., $\lambda = 46°16'$ E.

It has proved impossible to obtain any information concerning seismologic stations supposed to be maintained at Barrackpur, Bengal, India; Huelva, Spain; Pontevedra, Spain; Rangoon, Burma; Sucre, Bolivia; Taungoo, Burma; and the Island of Teneriffe.

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ARCTIC REGIONS

Disko Island (Greenland), Reykjavik (Iceland), Advent Bay (Spitzbergen).

ATLANTIC OCEAN

Ponta Delgada (Azores), Cape Verde Islands, Ascension Isl., St. Helena Isl.

EUROPE

BRITISH ISLES

Blackburn, Cardiff, Dyce, Edinburgh, Eskdalemuir, Liverpool, Oxford, Paisley, Richmond, West Bromwich.

HOLLAND

De Bilt.

BELGIUM

Quenast, Uccle.

FRANCE

Besançon, Clermont-Ferrand, Le Mans, Lille, Marseilles, Paris, Pic du Midi, Strasbourg, Toulouse.

SPAIN

Alicante, Almeria, Cartuja, Fabra, Malaga, Rio Tinto Mines, San Fernando, Toledo, Tortosa.

PORTUGAL

Coimbra, Lisbon.

NORWAY

Bergen.

SWEDEN

Abisko, Upsala.

GERMANY

Aachen, Biberach, Bochum, Breslau-Krietern, Darmstadt, Durlach, Freiberg i. Br. Göttingen, Hamburg, Heidelberg, Heligoland, Hof, Hohenheim, Jena, Jugenheim, Klausthal, Königsberg, Königstein i. T. Leipsig, Munich, Nördlingen, Plauen-Vogtland, Potsdam.

SWITZERLAND

Chur, Davos, Neuchatel, Zürich.

ITALY

Benevento, Caggiano, Capannoli, Carloforte, Casamicciola, Catania, Chiavari, Domodossola, Florence (3), Foggia, Genoa, Livorno, Messina, Milan, Mileto, Mineo, Moncalieri, Montecassino, Naples (3), Padua, Pavia, Pola, Porto d'Ischia, Porto Maurizio, Rocca di Papa, Rome, Salò, San Luca, Siena (2), Subiaco, Taranto, Trenta, Trieste, Turin, Urbino, Venice, Verona.

POLAND

Krakow (2), Lwów.

CZECHOSLOVAKIA

Eger, Stará Ďala, Ungvár.

AUSTRIA

Graz, Innsbruck, Kremsmünster, Vienna.

HUNGARY

Budapest, Kalocsa, Kolozsvar.

JUGOSLAVIA

Belgrade, Laibach, Sarajevo, Zagreb.

Fiume. Constantinople.

ROUMANIA

Bucharest, Cernauţi, Cluj, Teniţoara.

BULGARIA

Sofia.

GREECE

Aigion, Athens, Chalcis, Kalamata, Zante.

RUSSIA

Achalkalaki, Baku, Balakhany, Batum, Borzum, Derbent, Ekaterinburg, Makejevka, Moscow, Nicolajef, Piatigorsk, Pulkova, Šemakha, Tiflis.

MEDITERRANEAN SEA

Malta.

AFRICA

Alger-Bouzaréah (Algiers), Helwan (Egypt), Asmara (Eritrea), Accra (Gold Coast), Johannesburg (Cape of Good Hope).

ASIA

RUSSIA

Irkutsk, Kabansk, Kašgar, Krasnojarsk, Krasnovodsk, Marituj, Taškent, Tsita, Vernyi, Vladivostok, Zurnabad.

ASIA MINOR

Beirut (2), Harpoot.

INDIA

Bombay, Calcutta, Colaba, Colombo, Dehra Dun, Kodai Kanal, Simla.

CHINA

Dairen, Tsingtao, Zi-ka-wei.

JAPAN

Aomori, Asahigawa, Chosi, Fukuoka, Gifu, Hakodate, Hamada, Hamamatsu, Hikone, Hiroshima, Hokoto, Ishigakijima, Jinsen, Kagoshima, Kanayama, Kanazawa, Karenko, Kobe, Koshun, Kumamoto, Kyoto (2). Maebashi, Matsumoto, Matsuyama, Mito, Miyazaki, Mizusawa, Mukaiyama, Naha, Nagano, Nagasaki, Nagoya, Niigata, Numazu, Oita, Osaka, Otomari, Saga, Sakai, Sapporo, Shionomisaki, Tadotsu, Taichu, Taihoku, Tainan, Taito, Takayama, Takushima, Tokyo (2), Tsu, Tsukuba-San, Yagi, Yamagata.

INDIAN OCEAN

Keeling Island, Mahe (Seychelles Isls.), Pamplemousses (Mauritius Isl.), Tananarive (Madagascar).

EAST INDIES

Ambulong, P. I., Baguio, P. I., Butuan, P. I., Irosin, P. I., Mambajao, P. I., Manila, P. I., Tigaon, P. I., Batavia, Java, Malabar, Java.

AUSTRALIA

Perth, South Yarra, Sydney (2).

PACIFIC OCEAN

Guam, Honolulu (2), Volcano House, T. H., Fanning Isl., Apia, Samoa, Wellington, N. Z., Christchurch, N. Z.

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